SAN FERNANDO, CALIFORNIA, EARTHQUAKE OF 9 FEBRUARY 1971

BULLETIN 196

California Division of Mines and Geology
Sacramento, California

SAN FERNANDO, CALIFORNIA, EARTHQUAKE OF 9 FEBRUARY 1971

GORDON B. OAKESHOTT, *Editor*
CALIFORNIA DIVISION OF MINES AND GEOLOGY

BULLETIN 196
California Division of Mines and Geology
Resources Building, Sacramento, California
1975

California Division of Mines and Geology contributions to this Bulletin were prepared in cooperation with the County of Los Angeles, Department of the County Engineer; and the Los Angeles County Flood Control District.

STATE OF CALIFORNIA
RONALD REAGAN, GOVERNOR

THE RESOURCES AGENCY
NORMAN B. LIVERMORE, JR., *SECRETARY*

DEPARTMENT OF CONSERVATION
RAY B. HUNTER, *DIRECTOR*

DIVISION OF MINES AND GEOLOGY
WESLEY G. BRUER, *STATE GEOLOGIST*

Bulletin 196

THE COVER

Lower San Fernando Dam: Severe sliding in this old, hydraulic earth-fill dam posed a major flood threat. *Los Angeles Times photo.*

CONTRIBUTING AUTHORS

Ralph Alewine

Clarence R. Allen

Alexander K. Baird

Allan G. Barrows

Shawn Biehler

Bruce A. Bolt

Glenn A. Brown

Wesley G. Bruer

Robert O. Burford

California Division of Highways

Rodger H. Chapman

Gordon W. Chase

William K. Cloud

R. W. Clough

C. J. Cortright

Lawrence L. Davis

C. Martin Duke

Perry L. Ehlig

James R. Evans

Richard B. Fallgren

B. S. Gopalakrishnan

R. B. Grannell

Roger W. Greensfelder

T. C. Hanks

Mary R. Hill

Donald E. Hudson

James E. Kahle

W. T. Kinoshita

Los Angeles County Earthquake Commission

John F. Meehan

Donald F. Moran

Douglas M. Morton

Gordon B. Oakeshott

Howard W. Oliver

Joseph Penzien

Dwight D. Pollard

S. L. Robbins

Frederic I. Ross

Richard B. Saul

James C. Savage

Robert V. Sharp

James E. Slosson

Jay L. Smith

Karl V. Steinbrugge

Arthur G. Sylvester

F. Harold Weber, Jr.

Lewis R. West

James H. Whitcomb

CONTENTS

PLATES *

* Chapters 6-11, 13, and 17 and plates 2-5 were prepared in cooperation with the County of Los Angeles, Department of the County Engineer; and the Los Angeles County Flood Control District.

FOREWORD

At 6 a.m., on February 9, 1971, the Los Angeles, California, area was struck by a disastrous earthquake of Richter magnitude 6.5. First reports did not indicate how severe was the 'quake nor how extensive the damage; but, within minutes, police and other emergency agencies acted. In less than two hours, the American National Red Cross had shelters operating, and, within the same span of time, scientists were at work studying the effects of the earthquake.

Soon it became apparent that the communities of San Fernando, Saugus, and Sylmar, in the northwestern San Fernando Valley, sustained the greatest damage. Nearly all deaths attributed to the earthquake—a total of 64—were in these communities.

Seismological records showed that the main shock occurred at 14 h 00m 41.65 (GMT). Its epicenter was near latitude 34°24′ N and longitude 118°24′ W, in the San Gabriel Mountains. The focal depth was calculated to be 8.4 ± 4 km. There were 35 aftershocks with a Richter magnitude of 4.0 or more recorded within the first seven minutes following the main shock; aftershocks of similar magnitude continued through the year.

The San Fernando earthquake—as it has been called—occurred near the center of the largest concentration of strong-motion recording instruments in the United States. At that time, there were about 340 instruments in the area, which provided the largest number of strong-motion records ever written by any earthquake. One of them, an accelerograph located at Pacoima Dam, virtually at the epicenter, measured the strongest ground motion ever recorded.

In the long, geologic view, this earthquake was but one of a myriad of 'quakes that must have taken place during the uplifting of the Transverse Ranges, of which the San Gabriels are a part. It was one of many movements that, totalled together, pushed the mountains upward a matter of miles.

Yet it is the smaller parts of this small geologic event that tell the story. Geologists spent many months measuring surface effects in detail to prepare the most complete document ever made of these earthquake features—a document that will be studied for years to come.

Shattered ridge tops—"plowed ground"—noted in earthquakes before but not in such profusion, indicated a concentration of shaking energy along narrow hills capped by thin sedimentary beds. Many such areas were mapped by geologists of the California Division of Mines and Geology in the year following the earthquake; one paper in this volume suggests a means by which the required energy might have been concentrated on the ridge tops.

Painstaking care allowed the mapping of the many fault traces and surface breaks (see plate 3) which formed an intricate pattern. Geologists combined field work and photogeology to map thousands of landslides triggered or reactivated by the shocks. The landslides were, fortunately, in the hills where there were few buildings to damage.

The destruction of buildings and tragic loss of life dramatically revealed the unsafe construction of some buildings. Total monetary loss from the earthquake amounted to an estimated $511 million, or $71 per person in the Los Angeles area.

In spite of this high loss, most buildings behaved very well. No public school building collapsed, although several that were built before the "Field act"—the law requiring that school buildings be built to earthquake-resistant construction standards—had to be razed. Very few structural defects developed in schools meeting these standards, and no school was seriously damaged. Had students been in any of these earthquake-resistant schools at the time of the earthquake, they would have been safe.

Most of the buildings designed and constructed to similar standards held up well. On the whole, connections between different parts of structures were the weakest.

The San Fernando earthquake has given us an opportunity to reassess our position in regard to earthquakes. Engineers have had an opportunity to reassess building codes, seeking out weaknesses and re-examining the provisions that proved good; geologists and seismologists have been able to reassess their perception of crustal response to earthquakes, and to reconsider how they, as scientists, should organize their study of any earthquake; agencies of various levels of government have reassessed their position in regard to earthquake safety.

Such study and reassessment does pay off, as the San Fernando earthquake has shown. The deaths, unfortunate though they were, nearly all took place in buildings that were not built to earthquake-resistant codes. The casualty factor in personal residences in the shaken area was less than one person per million. Since most people were at home, this is a phenomenally low casualty rate, and clearly reflects the wisdom of good building codes and thorough enforcement. Had such a strong earthquake struck in as highly a populated area where good construction based on the best available knowledge did not prevail, the tragedy would have been nearly incalculable.

Mary Hill

NOTICE

This Bulletin, which has been in preparation for nearly 4 years, contains papers submitted by 48 authors. Some of the papers were received as early as July 1971 and others were received as late as July 1973.

The "Consolidated References" in the Bulletin include references that were submitted by each author with his paper. Even though new data and new references may have come to hand, no opportunity was afforded the authors to up-date their manuscripts.

Editor
August 1974

Section 1

Geology and Geophysics

CHAPTER 1

Tectonic Setting of the San Gabriel Mountains

by D. M. Morton [1] and A. K. Baird [2]

The San Gabriel Mountains, a part of the Transverse Range Province and perhaps part of a much larger transverse structural province, have undergone repeated deformation giving rise to east-trending structures. Structures within pre-Mesozoic batholithic rocks, and structures and chemistry of batholithic rocks, indicate these east-trending structures had their inception by Late Cretaceous time, and, perhaps, much earlier. Deformation resulted in the formation of depositional basins, folds, and faults.

A frontal fault system, the Malibu Coast-Cucamonga, marks the southern margin of the western Transverse Ranges and separates basement with abundant Precambrian rocks in the San Gabriel Mountains from basement rocks in the Peninsular Ranges which do not contain rocks of known, or even suspected, Precambrian age. The San Gabriel Mountains have been uplifted along the frontal fault system, which has had a dip-slip component totaling at least 10,000 feet in several localities.

Considerable evidence indicates the fault system along the entire south front of the San Gabriel Mountains has undergone repeated Quaternary displacements. These displacements have consisted largely, if not entirely, of reverse dip-slip movement. At the present time, these movements may be relieving elastic strain accumulating on the San Andreas fault zone.

GENERAL

The San Gabriel Mountains, a lenticular range about 60 miles long, are bounded by major fault zones on the north (San Andreas), south (Cucamonga), and southwest (Sierra Madre). Soledad Canyon forms the northwestern topographic boundary. Plutonic and metamorphic basement rocks, which comprise most of the mountains, range in age from over 1700 m.y. (Silver, 1966, 1971) to 20 m.y. (Hsu, *et al.*, 1963).

The other ranges of prominence are the San Bernardino, Santa Monica, and Santa Ynez. These are physiographically and structurally anomalous east-trending mountains which are set athwart the otherwise consistent northwest grain of the state. Evidence indicates this east-trend pre-dates considerably the geomorphologically youthful mountain ranges. Their present physiography merely reflects the much older structure. The Province extends from offshore, where sea floor highlands form the channel islands on the continental borderland, eastward some 300 miles to the vicinity of the Little San Bernardino Mountains, where physiographic expression of the province becomes vague (plate 1). The southern margin of the Province is well delineated by a frontal fault system: the combined Malibu Coast-Cucamonga fault complex. This complex, from west to east, consists of the Malibu Coast, Santa Monica, Raymond Hill, Sierra Madre, and Cucamonga faults. The Banning fault is assumed to be an eastward continuation of the frontal fault system, offset to the southeast by the San Jacinto fault. The northern margin of the Province is less clearly defined except for the steep north slope of the San Gabriel Mountains, which provides a sharp physiographic boundary (at the San Andreas fault) against the Mojave Desert Province.

On a large scale, the Transverse Ranges Province has long been considered part of a major structural feature that extends eastward into Texas. This was recognized prior to 1902 by R. T. Hill (1902, p. 172–173) as a "transverse line." Later Ransome (1915, p. 294–295) drew attention specifically to Hill's "transverse line" to which he gave the name "Texas Lineament." Ransome noted the eastward and westward parts are relatively well defined (he considered Point Conception as the western terminus); but, over the total length, it is relatively vaguely defined "and perhaps in part imaginary . . ." (p. 295). This transverse structure (Texas Lineament) has received repeated attention and comment (for example, R. T. Hill, 1928; Baker, 1933, 1934; Albritton and Smith, 1957; and Muehlberger, 1965).

In addition to the Texas Lineament, speculation has revolved about the coincidence of the southern margin of the province with the Murray fracture zone. Some have questioned whether the alignment is fortuitous (for example, Gilluly, 1970, p. 64, 66–67, 68–69; Menard, 1955, p. 1197). However, Vacquier, *et al.* (1961, p. 1253), state all magnetic and bathymetric expression of the Murray fracture zone stops east of 124° W. longitude with a 4° longitudinal gap between the eastern end of the zone and the Channel Islands. This has been supported by von Huene (1969, 1971) who, from continental shelf data, found Transverse Range structures developed since late Miocene or early Pliocene time. He considered, however, that there may have been a more extensive pre-Miocene Murray fracture system extending on shore.

Though the question of a definite or genetic relationship to larger structural features (that is, the Texas Lineament and Murray Fracture Zone) is unresolved, the Transverse Ranges Province, as an entity, remains a structural feature of first-order importance within California.

A notable feature of the Province is the abundance of rocks of Precambrian age. South of the Malibu Coast-Cucamonga fault system (in the Peninsular

[1] Formerly with the California Division of Mines and Geology; now with the U.S. Geological Survey.

[2] Geology Department, Pomona College.

Ranges Province), there are no known, or even suspected, Precambrian age rocks (Baird, *et al.*, 1971). Furthermore, published dates for Mesozoic granitic rocks in the San Gabriel Mountains, by both K-Ar method (Evernden and Kistler, 1970) and Pb method (Silver, 1971), give ages of 10 to 45 m.y. less than the Mesozoic granitic rocks in the Peninsular Ranges Province. These facts suggest that a fundamental division exists within basement rocks of southern California. The line marking these differences is the frontal fault system of the Transverse Ranges to the west; to the east, where the boundary curves southward, it coincides with the Salton Trough.

AGE OF THE TRANSVERSE STRUCTURES

Throughout the Transverse Ranges Province, east-trending structures predominate. In metamorphic rocks this common orientation stands out in contrast to the quite uniform northwest structural orientation in the Peninsular Ranges Province (Baird, *et al.*, 1971). Some east-trending structures have obviously been in part produced or intensified during Tertiary deformations (for example, the eastern Santa Monica Mountains area as shown by Hoots, 1930); however, most east-west structures had their origins prior to the emplacement of Mesozoic plutonic rocks as demonstrated by truncated foliation and/or layering against the plutonic rock bodies.

Many of the granitic plutons have an east-trending elongation and an internal foliation and/or layering with a similar east-trend, which is again in marked contrast to the northwest trend in the plutonic rocks and structures of the Peninsular Ranges Province. Moreover, the areal distribution of major elemental chemistry and specific gravity of the rocks directly coincides with the batholithic structures in the two provinces. Such trends exist throughout the San Gabriel and San Bernardino Mountains, whereas northwest trends occur throughout the Peninsular Ranges (Baird, *et al.*, 1970).

For post-batholithic rocks, east-trends predominate throughout the Transverse Ranges and again stand in contrast to the northwest trends in the Peninsular Ranges to the south and the Coast Ranges to the north (Baird, *et al.*, 1971). Crowell (1971, p. 106) stated that sedimentary patterns for the Cretaceous, Paleocene, and Eocene suggest an east-trending fracture system for those times. Winterer and Durham (1962) believed the southeastern Ventura basin was probably a depositional site during the Paleocene; Oakeshott (1958, p. 62) deduced that the eastern Ventura basin, including the Soledad basin, was in existence by late Eocene time; and Edwards (1971) presented evidence for deposition in the Ventura-Soledad basin by late Eocene time, accompanied by deformation and a north-south oscillation of the shoreline. However, Yerkes and Campbell (1971) indicated pre-middle Miocene shorelines retained their north-northwest trend through the Transverse Ranges.

Clearly, since middle Miocene time, there has been deformation resulting in east-trending structures. In the western Santa Monica Mountains, Campbell, *et al.*, (1966, p. 5) showed that rocks of Late Cretaceous age were at least gently folded, apparently about a west-to-northwest axis prior to emplacement of a series of three detachment sheets during latest middle Miocene time. The detachment sheets were themselves later folded about an east-trending axis. Hoots (1930, especially cross-section E-E′) diagrammatically indicated repeated folding of the rocks in the eastern Santa Monica Mountains. His cross-sections show the Jurassic Santa Monica Slate to have been deformed about an easterly trending axis prior to the deposition of Upper Cretaceous rocks ("Chico"), with subsequent similar folding affecting, in sequence, "Chico" rocks, middle Miocene Topanga rocks, and finally the Modelo Formation of late Miocene age. From Pliocene time on, repeated east-trending deformation was common throughout the Transverse Ranges.

MAJOR FAULTS OF THE SAN GABRIEL MOUNTAINS

Inactive Faults

Vincent thrust. Perhaps the oldest recognizable fault in the Transverse Ranges is the west- to northwest-striking Vincent thrust together with assumed related faults of the San Gabriel and San Bernardino Mountains area. Ehlig (1968) considered the cataclastic deformation associated with the Vincent thrust to have occurred probably in Late Cretaceous after the emplacement of Mesozoic batholithic rocks. He believed the upper plate moved northeastward. Burchfiel and Davis (1970) considered the Vincent thrust to be part of a large two-sided thrust complex (*zwischengebirge*) centered on the Mojave Desert, northeast of the San Gabriel Mountains. They inferred the upper plate to have moved westward with a minimum displacement greater than 75 miles.

Large-magnitude east-trending and north-dipping shear zones are present in the frontal part of the southeastern San Gabriel Mountains (Alf, 1948; Hsu, 1955). Here both granitic and high-grade metamorphic rocks have been cataclastically deformed, probably during the last part of Cretaceous time. Orientations of minor structures within these rocks indicate a major component of dip-slip movement (D. M. Morton, unpublished mapping). Both the temporal and genetic relations of these cataclastic rocks to those of the Vincent thrust are unknown.

San Gabriel fault. The San Gabriel fault, now considered by many to be inactive, is an important younger fault with Tertiary movement. Crowell believed it to have had a right lateral displacement of about 20 miles and a dip-slip movement of as much as 14,000 feet (1952, 1954). Movement on this fault occurred from early late Miocene time to about the end of the Pliocene epoch and was locally reactivated during the Pleistocene (Crowell, 1952, 1954). Ehlig (1966, p. 60) found basement rock contacts offset 13 miles in the central San Gabriel Mountains along this fault. However, Paschall and Off (1961), in the eastern Ventura basin, have deduced an alternative sense of movement for the San Gabriel fault. They found evidence for at least four alternations of uplift and subsidence, each of which included thousands of vertical feet of movement during the Tertiary, and suggested that the total fault movement was predominantly, if not entirely, vertical.

Faults of the San Andreas System

There are other faults in the San Andreas system in addition to the San Andreas fault itself in the eastern San Gabriel Mountains. Oldest of these is the apparently inactive Punchbowl fault, which merges with the San Andreas in the Devore area and has a somewhat sinuous trace northwestward to the Devils Punchbowl area (Dibblee, 1968). For most of its length, it is characterized by the presence of sheared gneiss within the fault zone. West of the Punchbowl fault is the active Glen Helen fault, exposed in the west side of lower Cajon Creek. It extends southeastward into the San Bernardino Valley, and to the northwest it turns abruptly westward entering Lytle Creek where it may join the San Jacinto fault. The San Jacinto fault, west of the Glen Helen fault, enters the San Gabriel Mountains near the mouth of Lytle Creek. Branches of the San Jacinto strike westward to west-southwest paralleling the length of the mountain range. Dibblee (1968) suggested that the San Jacinto fault dies out in the upper reaches of the creek. Several other apparent right-lateral faults are west of the San Jacinto fault.

Left-Lateral Faults

Northeast-striking left-lateral faults occur in the eastern San Gabriel Mountains in the vicinity of San Antonio Canyon. Two of these offset the Vincent thrust about 4 miles (Dibblee, 1968; Rogers, 1965) and a third offsets the Punchbowl fault (D. M. Morton, unpublished mapping). Farther west in the Pacifico Mountain area are several left-lateral northeast-striking faults, including the Transmission Line, Pole Canyon, and Magic Mountain faults (Oakeshott, 1958; Jennings and Strand, 1969), with lateral displacement of the order of 1 to 2 miles.

Transverse Faults

The most impressive east-trending structure of the Transverse Ranges Province is the frontal fault system which is the boundary between the greatly contrasting basement rocks of the Transverse Ranges—especially the San Gabriel Mountains—with the Peninsular Range Province to the south. It extends, east to west, from the San Jacinto fault to offshore in the Malibu area. East of the San Jacinto fault, the frontal fault system appears to be offset by the San Jacinto fault about 15 miles right laterally, where, in the San Gorgonio Pass area, it is termed the Banning fault (Allen, 1957; Sharp, 1967). Immediately west of the San Jacinto fault the prevailing name for the frontal fault is the Cucamonga; further west, in the Azusa-Sierra Madre area, it is the Sierra Madre; through Pasadena, the Raymond Hill; in the vicinity of Beverly Hills, the Santa Monica; and in the Malibu area, the Malibu Coast fault. Between Monrovia and Sierra Madre the system branches to the west (or the two merge to the east) with the main (principal) continuation being westward along the Raymond Hill fault. The second fault zone extends to the northwest and, in turn, branches into two fault zones. The northernmost zone, which enters the San Gabriel Mountains, is apparently a branch of the San Gabriel fault (Oakeshott, 1954), although some have considered it to be the continuation of the Sierra Madre fault (for example, Bailey and Jahns, 1954). The southern fault zone lies between the Verdugo Mountains, to the south, and the San Gabriel Mountains and projects westward into northern San Fernando Valley area (Bailey and Jahns, 1954; Oakeshott, 1954, 1958), and has been considered to be the Sierra Madre zone (Oakeshott, 1958).

From the Sylmar area, where the major breaks have been termed the Lopez fault (M. L. Hill, 1930) and Hospital fault (Oakeshott, 1958), the zone continues westward as the Santa Susana fault (thrust) into the Santa Susana Mountains. South of the Santa Susana Mountains several east-trending faults such as Mission Hills, Granada Hills, and Northridge Hills (Wentworth and Yerkes, 1971, p. 8) are part of the frontal fault system. For the structural details of the northern San Fernando Valley area, see Oakeshott, this Bulletin.

Throughout its extent the frontal fault system is characterized by moderate to shallow northward dips into the mountains. Only in the area immediately west of Little Santa Anita Canyon do vertical dips prevail (Morton, 1971) but these shortly pass into northward-dipping faults to the west (Saul, 1971).

Magnitude of displacement. As evidenced by the abruptly rising mountain front of the San Gabriel Mountains, there must have been considerable recent reverse dip-slip movement on the frontal fault system. Dip-slip separation on the Cucamonga fault segment can only be estimated. Eckis (1928, p. 226) considered a vertical displacement of 4,000 to 5,000 feet; this is probably a very conservative figure.

In the Azusa-Duarte area, two exploratory wells drilled about a mile and a half south of exposed granitic rocks bottomed at depths of 6,914 feet and 7,854 feet in middle Miocene Glendora Volcanics and Topanga Formation respectively (California Division of Oil and Gas, 1962, 1969). These rock types crop out adjacent to the well sites where they form a large overturned synclinal structure produced by movement on the frontal fault (Morton, 1971; Shelton, 1955). Basement rocks rise abruptly 3,000 feet above the valley floor, suggesting the total vertical displacement here is on the order of 10,000 feet.

At the mouth of Big Santa Anita Canyon, thrusting of gneiss over older alluvium (Morton, 1971) suggests vertical displacements on the order of 4,000 feet on a northern branch of the Sierra Madre fault zone, or a southern branch of the San Gabriel fault. Offset basement on the Raymond Hill fault, to the south, is probably of the same order of magnitude.

More spectacular yet is the displacement indicated by the available information from Sunray Oil Company's Stetson-Sombrero well #1. This well was drilled 1 mile north of Sylmar and about half a mile south of granitic rock basement (Oakeshott, 1958). It had a total depth of 12,027 feet and apparently was wholly within nonmarine Saugus Formation of Quaternary age (Oakeshott, 1958). However, rumors say that the well bottomed in rocks bearing upper Pliocene brackish water fauna. This would suggest the total sedimentary section adjacent to the mountain front may be of the order of 20,000 feet. A similar geologic setting is indicated by Richfield Oil Corporation's T.I. & T.1 well, drilled about 2 miles west of the Stetson-Sombrero #1. This well, located just south of the Santa Susana fault, was entirely within continental sediments, presumably Saugus Formation, for its entire depth of 8,207 feet.

Yerkes and Campbell (1971) considered the left-lateral component of movement for the frontal fault system to be more than 50 miles and to have been initiated in mid-Miocene time in response to sea-floor spreading (Campbell and Yerkes, 1971).

Recency of fault movement. Throughout the extent of the frontal fault zone, there is abundant evidence for displacement during or after Pleistocene time. Wentworth, *et al.* (1970), indicate that, for most of the frontal fault system west of Glendora, there is evidence for fault displacement between 11,000 and 300,000–500,000 years ago.

In the Lytle Creek area, basement has been thrust over steeply dipping continental beds of probable Pliocene or early Pleistocene age. West of Lytle Creek, the alluvial fan at the mouth of Day Canyon is cut by several scarps, the youngest of which is 10–15 feet high and 3 miles long. An older modified scarp is 120 feet high, and a yet older scarp in the alluvial fan is 200 to 280 feet high (Eckis, 1928, p. 230). Two drainages west, at the mouth of Cucamonga Canyon, there are two scarps in alluvial fan deposits, a younger 10-foot and an older 60–75 foot scarp (Eckis, 1928, p. 229–230). Several miles south of the mountain front are several modified scarps (for example, Red Hill and Indian Hill) in late Pleistocene alluvium.

In the Azusa-Duarte area, faulting was contemporaneous with and followed the deposition of the late Pleistocene San Dimas Formation (Morton, 1971). Such physiographic breaks as Bradbury Mesa may be the expression of considerably younger modified scarps.

North of Arcadia, gneiss (Precambrian?) has been thrust over Quaternary (late Pleistocene?) alluvium at the mouth of Santa Anita Canyon (Morton, 1971), and to the south the Raymond Hill fault forms a scarp in alluvium 50 to 150 feet high (Eckis, 1934, p. 69). Proctor *et al.* (1970, p. 8) report 11 occurrences of basement rocks thrust over Quaternary deposits along a 22-mile long segment of the frontal fault system west of Glendora.

Relation of movement on the frontal fault system to the San Andreas system. Some consider recent movement on the frontal fault system is in response to accumulating elastic strain on the San Andreas fault system (for example, Don L. Anderson, as quoted in *California Geology*, 1971, v. 24, p. 73). The faulting on the frontal faults is believed to be produced by north-south compression, which is a component of strain normally producing right lateral strike-slip movement on the more westward-striking part of the San Andreas fault as it enters the Transverse Ranges Province from the north. If this is the case, the present day strain release is probably taking advantage of the older east-trending break in the Transverse Ranges structure.

CHAPTER 2

Geologic Framework of the San Gabriel Mountains[1]

by Perry L. Ehlig[2]

Although the San Fernando earthquake was unpredictable in its location and timing, the faulting and associated uplifting of the mountains were not unexpected. The San Gabriel Mountains have long been recognized as a young, tectonically active range. They form an impressively rugged barrier, 60 miles long and about 20 miles wide, separating the Mojave Desert on the north from the low-lying San Fernando, San Gabriel, and Pomona valleys on the south. The southern margin of the range juts up abruptly from the adjoining alluvial valleys. It is controlled by a complex series of interconnecting, northward-dipping reverse faults including the fault which caused the San Fernando earthquake. The northern margin of the range nearly coincides with the trace of the San Andreas fault but is controlled by arching and differential erosion, as well as faulting. The interior of the range is deeply dissected by streams. The most prominent peaks rise 8000 to 10,000 feet above sea level in the eastern and north-central parts of the range and 5000 to 7000 feet above sea level in the south-central and western parts. The highest peak is 10,062-foot Mount San Antonio.

SUMMARY

The San Gabriel Mountains are a major east-west-trending range within the Transverse Range province of southern California which contain 900 square miles of exposed igneous and metamorphic rocks (see plate 1 in pocket).

Precambrian gneiss and amphibolite form the host for several ages of intrusive rocks within the central and western parts of the range. Precambrian anorthosite and related rocks crop out in a highly deformed layered intrusion of 80 square miles in the western part of the range. Permian-Triassic Lowe Granodiorite forms a northwest-trending, compositionally zoned pluton of 100 square miles within the central and northwestern parts of the range. Mesozoic granitic rocks and associated migmatite are abundant in the center of the range.

In the northeastern part of the range, the terrane is truncated by the southwestward-dipping Vincent thrust fault. A thick zone of mylonitic rocks is developed along the thrust. Mesozoic(?) Pelona Schist underlies the thrust. The 10,000 feet of exposed schist is derived from well-bedded graywacke and shale interbedded with basaltic tuff and chert. The schist underwent metamorphism to the greenschist-facies grade synchronous with burial beneath the Vincent thrust.

The southwestern, eastern, and extreme northeastern parts of the range contain Paleozoic(?) metasedimentary rocks that were extensively converted to gneiss and migmatite during intrusion of Mesozoic granitic rocks. These rocks are in fault contact with rocks in the interior of the range.

The internal structure of the San Gabriel Mountains is complicated by the intermingling of igneous and metamorphic rocks, by multiple episodes of metamorphism, and by faulting. The orientation of foliation is variable but commonly strikes northwestward at about 45 degrees to the long axis of the range. The Vincent thrust underlies much of the range. Rocks of the upper plate of the thrust may be a relatively thin veneer concealing the structure deep within the range.

Several major high-angle faults transect the range. The most prominent include the San Gabriel, San Jacinto, and San Andreas faults, all of which strike between west and northwest and have right-lateral displacements of many miles.

The San Gabriel Mountains owe their present height and configuration to uplift since the mid-Pleistocene. Uplift has been accomplished by reverse faulting along the southern front of the range and arching along the northern margin. The San Fernando earthquake resulted from displacement along the most westerly segment of the frontal fault system.

The San Gabriel Mountains are part of a continuous uplift that extends eastward into the San Bernardino Mountains and westward into the Santa Susana Mountains. The uplift is superimposed upon older structures rather than being controlled by them. The uplift is a product of crustal shortening and may result from compression along the bend in the San Andreas fault or from clockwise rotation of Baja California.

GEOLOGIC SETTING

The relatively simple geomorphic boundaries of the San Gabriel Mountains are superimposed upon a geologically complex terrane cut by several major faults. Most of the exposed rocks are of metamorphic and intrusive igneous origin and range from Precambrian to Miocene. Cenozoic sedimentary rocks are locally present near range margins, particularly near the west end in the area affected by the San Fernando earthquake and on the north adjoining the San Jacinto and San Andreas faults.

[1] Manuscript submitted for publication November 22, 1971.
[2] California State University, Los Angeles.

The oldest terrane includes the central and northwestern parts of the range. Here, remnants of Precambrian gneiss are intruded by (1) a Precambrian anorthosite-gabbro-syenite complex, (2) Lowe Granodiorite of Permian-Triassic age, (3) metamorphosed dikes of basalt, andesite, and rhyolite, and (4) Mesozoic granitic rocks. In the northeastern part of the range, this old terrane is truncated by the Vincent thrust fault which dips southwestward beneath it and is marked by a thick zone of mylonitic and retrograde metamorphic rocks. The Mesozoic(?) Pelona Schist underlies the Vincent thrust and crops out between it and the San Jacinto fault to the northeast.

Photo 1. Precambrian anorthositic gabbro with vertical compositional layering. Anorthosite pegmatite forms light-colored tongue. Layers believed to have formed by crystals settling onto flat floor of magma chamber. Vertical position due to subsequent tilting. Angeles Forest Highway south of Boughman Spring.

The southwest, east, and northeast parts of the range are underlain by crystalline rocks which differ from those in the interior and are separated from them by strike-slip faults. To the south of the San Gabriel fault, the southwestern part of the range and the nearby Verdugo Mountains and San Rafael Hills are underlain by crystalline rocks consisting of remnants of Paleozoic(?) metasedimentary rocks interspersed through gneiss, migmatite, and granitic rocks. A similar terrane containing a better preserved metasedimentary section occurs east of the San Antonio fault in the eastern part of the range; however, it is bounded on the south by a belt of mylonite and granulite-facies rocks. Blue Ridge, situated between the San Jacinto and San Andreas faults, is composed of Pelona Schist. Pinyon Ridge, northwest of Blue Ridge, is composed of gneiss, migmatite, and granitic rocks. The terrane north of the San Andreas fault contains Paleozoic(?) marble immersed in gneiss, migmatite, and granitic rocks.

The eastern end of the range contains stocks and dikes of light-colored, fine- to medium-grained massive quartz monzonite. Dikes and sills extending from the main bodies change into quartz-latite porphyry with a conspicuous decrease in grain size. The quartz monzonite is of special interest because it intrudes the Pelona Schist and Vincent thrust and has generally been assumed to be of late Cretaceous age. Dating by the K-A and Rb-Sr methods indicates it is early Miocene in age (Hsu *et al.*, 1963).

Middle Miocene dikes of andesite, basalt, and diabase are locally common in the southern and eastern parts of the range.

ROCK FORMATIONS

Precambrian Gneiss

The oldest dated rocks in the region are quartzofeldspathic gneisses and amphibolite exposed in the Soledad Basin northwest of the San Gabriel Mountains. Uranium-lead isotope ratios in zircon indicate some of these rocks are 1.7 billion years old (Silver, 1971). Gneiss that may have been part of the same Precambrian terrane occurs in many places within the range but is generally affected by younger metamorphism and igneous intrusions.

One of the most distinctive units is the Mendenhall Gneiss described and named by Oakeshott (1958, p. 21–29). This gneiss is mainly exposed in the western part of the range north of the San Gabriel fault and south of the anorthosite complex. It was subjected to high temperature granulite-facies metamorphism 1.4 billion years ago (Silver, 1963). During this metamorphism, pre-existing gneiss, amphibolite, and granitic rocks were converted to mineral assemblages consisting of pyroxene, garnet, perthitic feldspars, and blue quartz. In many areas Mesozoic metamorphism has converted the pyroxene and garnet to hornblende and biotite; however, some of the blue quartz, antiperthite, and distinctive relic textures have been preserved. Remnants of the Mendenhall Gneiss also occur between the north and south branches of the San Gabriel fault north of Altadena and in the north-central part of the range.

Compositionally layered quartzofeldspathic gneiss and amphibolite having a complex history but showing no evidence of granulite-facies metamorphism are widely distributed in the east-central and southeast-central parts of the range. These are probably Precambrian but have not been dated.

Anorthosite-Gabbro-Syenite Complex

A structurally complex body of anorthosite and related rocks is exposed over an area of about 80 square miles in the western San Gabriel Mountains. The complex is described in reports by Miller (1931, 1934); Oakeshott (1937, 1954, 1958); Higgs (1954); and Crowell and Walker (1962). Purplish gray and blue-gray to white andesine anorthosite is the most abundant rock type. Next in relative abundance is gabbro, in which the pyroxene has been replaced by amphibole, and syenite, part of which contains blue quartz. Many of the rocks are exceptionally coarse grained and have unusual textures.

This complex was emplaced 1.22 billion years ago (Silver, 1963, 1971). Recent studies by Carter (1971) indicate the complex was initially stratiform with prominent compositional layering produced by gravitational settling of crystals. The structure has subsequently become complex as a result of several episodes of deformation.

Metamorphosed gabbro, pyroxenite, and peridotite, which were once part of the main body, occur as pendants in Lowe Granodiorite and Mesozoic granitic rocks in the northern and east-central parts of the range.

A tectonic inclusion, more than 2 miles long and several hundred feet thick, of extensively mylonitized anorthosite and anorthositic gabbro occurs along the Vincent thrust fault in the northeastern part of the range. It was probably dragged along the sole of the thrust from an anorthositic terrane that once existed to the north of the San Gabriel Mountains but has subsequently been displaced by the San Andreas fault. The probable offset source terrane (Crowell, 1962) is presently exposed on the north side of the San Andreas fault in the Orocopia Mountains, 130 miles southeast of the San Gabriel Mountains.

Lowe Granodiorite

The Lowe Granodiorite crops out in a northwest-trending pluton exposed over an area of about 100 square miles in the central part of the range. The pluton is compositionally zoned and foliated parallel to its sharply defined, nearly vertical western margin. The margin consists of medium-grained hornblende diorite. This grades inward into a lighter colored coarse-grained hornblende quartz diorite. At an average distance of about half a mile east of the margin, orthoclase phenocrysts are conspicuous. Further to the east, hornblende diminishes, orthoclase phenocrysts become large—as much as 10 cm long—and abundant, and garnet is scattered through the rock. In the interior of the pluton, the rocks are nearly white and contain little besides feldspar. Some are largely composed of sodic oligoclase or albite. Throughout the pluton, the quartz content is low, generally varying on either side of 10 percent. The eastern margin of the pluton has been fragmented by younger granitic intrustions but appears to have been less regular than the western margin.

The Lowe Granodiorite was named and initially described by Miller (1934, p. 41–46). Detailed mapping has shown that part of the rocks he described and mapped are actually younger Mesozoic granitic rocks. The Parker Diorite, described by Miller (1934, p. 37–39) from exposures at the west end of the range, is actually the border facies of the Lowe Granodiorite.

Uranium-lead isotope ratios in zircon from Lowe Granodiorite indicate an age of about 220 $\pm$ 10 million years (Silver, 1971).

Metamorphosed Volcanic Dikes

Metamorphosed dikes are common in the Lowe Granodiorite and all older rocks but are absent from and truncated by the Mesozoic granitic rocks. Dikes derived from basalt and andesite are most common. They presently consist of hornblende and plagioclase with metamorphic textures and are referred to as amphibolite dikes. They are typically only a few feet thick and have straight, parallel walls. Some contain angular inclusions of the wall rock.

Metamorphosed rhyolite dikes containing scattered phenocrysts of quartz in an aphanitic groundmass occur in a belt several miles wide extending northward through the west-central part of the range. The most prominent dikes were emplaced along gently dipping joints and form sill-like sheets as much as 50 feet thick. Several of these can be traced for more than a mile without showing evidence of significant post-emplacement deformation.

In general, dikes in the western half of the range show little evidence of deformation since their emplacement. This suggests that the pre-Mesozoic rocks remained nearly rigid during the emplacement of Mesozoic granitic rocks. Many of the amphibolite dikes in the east-central part of the range are exten-

Photo 2. Lowe Granodiorite cut by amphibolite dikes. Faulting causes irregularities in dikes. Along Angeles Forest Highway in Aliso Canyon.

sively deformed. Part of the deformation post-dates the emplacement of cross-cutting granite aplite and pegmatite dikes and may be associated with the Vincent thrust.

Mesozoic Granitic Rocks

Mesozoic granitic rocks, ranging from quartz diorite to quartz monzonite in composition, intrude all other pre-Cenozoic rock units except the Pelona Schist. The quartz diorite is generally composed of 40 to 60 percent sodic andesine, 15 to 25 percent quartz, 10 to 25 percent hornblende and 5 to 10 percent biotite. The quartz monzonite generaly contains nearly equal amounts of quartz, calcic oligoclase, and orthoclase with 5 to 10 percent biotite as the only dark mineral. Granodiorite, an intermediate rock type abundant in many areas, is generally rich in biotite and poor in hornblende. All are medium grained.

The largest Mesozoic granitic intrusion crops out over an area of about 75 square miles in the central part of the range. There is complete gradation from quartz diorite to quartz monzonite within the pluton, but the most abundant rock is probably granodiorite. On the west, the intrusion forms a sharp, nearly vertical, north-trending contact with the Lowe Granodiorite and shows little evidence of stoping or assimilation. On the east, it has an irregular contact with large areas in which the adjoining rocks are brecciated or plastically deformed and intricately intruded by granitic material. Associated granitic aplite and pegmatite dikes are abundant in the terrane east of the pluton but absent from the terrane to the west. The southern part of the pluton has been offset westward along the San Gabriel fault. It is exposed in the vicin-

Photo 3. Metamorphosed gabbro (black) and foliated quartz diorite (gray) cut by quartz monzonite dikes (white). South of Islip Saddle in central San Gabriel Mountains.

ity of Mount Wilson and was named the Wilson Diorite by Miller (1934, p. 30).

A series of small plutons in the process of being unroofed and probably interconnected at depth trends east-west across the western part of the range a short distance north of the San Gabriel fault. Angular inclusions of wall rock are locally abundant along the margins of the plutons, suggesting emplacement by stoping. The composition of the plutons ranges from quartz diorite to quartz monzonite with granodiorite most abundant. An age of about 80 million years has been determined for granodiorite from one of the plutons (Carter, 1971).

Foliated quartz diorite and granodiorite are abundant in areas containing Paleozoic(?) metasedimentary rocks. They appear to have provided the heat required to convert the sedimentary rocks into gneiss and migmatite. Quartz diorite from Ontario Peak in the eastern part of the range has been dated at about 105 million years using the rubidium-strontium method (Hsu *et al*, 1963).

Pelona Schist

About 10,000 feet of Pelona Schist crops out in a southwest-dipping, right-side-up sequence between the San Jacinto fault and the Vincent thrust fault as described by Ehlig (1958, p. 83–133; 1968, p. 295–297). Metamorphism occurred under low-temperature dynamothermal conditions producing highly developed schistosity parallel to bedding. The dominant schist type is composed of quartz, albite, and muscovite with minor amounts of epidote, actinolite, and chlorite. It is gray because of finely disseminated graphite; it has been derived from sandstone, siltstone, and shale. Green albite-epidote-chlorite-actinolite schist, derived from basaltic tuff, is common in the upper part of the sequence. Quartzite derived from chert is a minor rock type.

Metamorphism of the Pelona Schist is interpreted to have occurred during the Late Cretaceous simultaneously with movement along the Vincent thrust (Ehlig, 1959; 1968, p. 297–298). The depositional age of the Pelona Schist is not known; however, the fact that it is of low metamorphic grade with a simple metamorphic history and is not intruded by Mesozoic granitic rocks suggests that deposition may have occurred only shortly before metamorphism.

The Pelona Schist forming Blue Ridge to the north of the San Jacinto fault contains the same lithology as that to the south but differs in detail. It is believed to have been displaced from Sierra Pelona by about 25 miles of right-slip along the San Jacinto fault (Dibblee, 1967, p. 114; Ehlig, 1968, p. 301).

Paleozoic(?) Metasediments and Associated Gneiss and Migmatite

The crystalline rocks in the southwestern part of the range, south of the San Gabriel fault, consist mainly of intermixed quartz diorite, granodiorite, gneiss, and migmatite. These rocks have a simple mineralogy consisting of various combinations of quartz, plagioclase, orthoclase, biotite, and hornblende. The migmatite, gneiss, and amphibolite were metamorphosed to their existing condition during intrusion of the quartz diorite and granodiorite and show no evidence of an earlier metamorphism.

Photo 4. Migmatite containing amphibolite pods derived from marble. East side of San Antonio Canyon.

Rocks of obvious sedimentary origin occur in scattered remnants within this terrane. These include marble, bedded calc-silicate rocks, quartzite, graphite schist, and aluminous schist. The metasedimentary rocks most commonly occur interlayered with gneiss or as lenses and pods in migmatite. This suggests the possibility that the gneiss and migmatite were also derived from sedimentary rocks.

Similar relationships exist in the eastern part of the range east of the San Antonio fault. However, the metasedimentary rocks are better preserved. A section containing 15 members with a total thickness of about 7300 feet has been delineated along the west side of Ontario Ridge (Ehlig, 1958, p. 51–57). The original lithology included quartz sandstone, dolomite, siltstone, and shale.

The terrane north of the San Andreas fault is extensively migmatized; however, mappable marble units are well preserved. One unit several hundred feet thick is exposed for a distance of 6 miles.

There is no direct evidence that the metasedimentary rocks are Paleozoic. However, in each of the three areas, the rocks appear to have undergone a single major metamorphism associated with intrusion of Mesozoic granitic rocks. There is no evidence of a complex history like that experienced by Precambrian rocks of the central and western San Gabriel Mountains. In addition, the lithology of the metasedimentary rocks is grossly similar to that of fossiliferous Paleozoic rocks in eastern California.

GEOLOGIC STRUCTURE

Transverse Range Problems

The origin of the east-west trend of the San Gabriel Mountains, as well as the other Transverse Ranges, is a major tectonic problem. Is the trend inherited from the structure of the pre-Cenozoic crystalline rocks that underlie the range, or is it a young feature superimposed upon the older structures? Also, what controls the boundaries of the range and the mechanics of its uplift? The answers to these questions are prerequisites to the development of a reliable model for predicting the location, nature, and intensity of faulting and earthquakes associated with range uplift. Partial answers can be obtained through a detailed reconstruction of the structural history of the rocks exposed within the range. Considerable progress has been made, but the results are still sketchy.

Structure Shown by Foliation

The abundance of igneous intrusions and the intermingling of igneous and metamorphic rocks have created a complex structure within much of the range. However, most of the rocks show foliation in relatively simple patterns. The orientation of foliation varies considerably from place to place but most typically strikes northwestward at about 45 degrees to the long axis of the range. Foliation in the east-central part of the range tends to dip southwestward at moderate angles, whereas that in the west-central and western parts tends to be nearly vertical or steeply inclined toward the east. Foliation in the southeastern part of the range differs notably from that in most other areas; it tends to strike nearly due east and dip northward at moderate to high angles.

Vincent Thrust Fault

Possibly the most important structural feature influencing the distribution of rocks at depth is the Vincent thrust fault. The thrust is exposed in the northeastern part of the range where it has displaced Mesozoic granitic and older rocks northeastward across the top of the Pelona Schist. The exposed thrust dips southwestward at about 30 degrees. Bedding in the underlying Pelona Schist is nearly parallel to the thrust surface in most areas. In view of this and the fact that erosion has exposed about 10,000 feet of schist without uncovering its base, the schist may extend a considerable distance to the south and west beneath the thrust. To put it another way, as the San Gabriel Mountains are eroded downward, the area of schist outcrop will expand southward and westward. Even if the schist extends only a few miles southward beneath the thrust, the thick zone of mylonitic rocks along the base of the thrust's upper plate must continue beneath all or most of the eastern part of the range. The displacement along the thrust is not less than 10 miles and is probably much greater than that. The reconstruction of the initial position of Pelona Schist exposed north of the San Jacinto fault indicates that it originally extended along the entire north side of the San Gabriel Mountains and connected to the schist exposed on Sierra Pelona to the west (Ehlig, 1968, p. 301). In this reconstruction, the Vincent thrust would also extend along the north side of the San Gabriel Mountains and connect with an equiv-

Photo 5. Mt. Baden-Powell viewed from east showing trace of Vincent thrust fault. Pelona Schist underlies thrust. Mylonitic rocks extend from base of thrust to crest of flat-topped ridge. Light layers are sills of Miocene quartz latite porphyry.

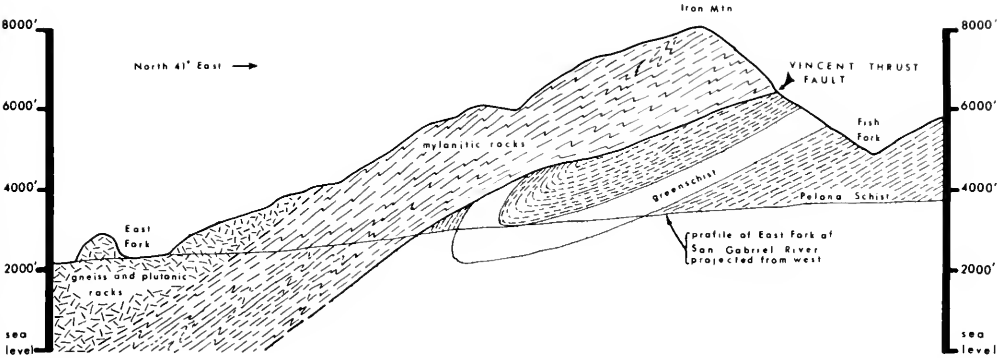


Figure 1. Geologic cross section showing Vincent thrust fault and drag fold in underlying Pelona Schist. Zone of mylonitic rocks developed from gneiss and plutonic rocks during thrust faulting.

alent thrust along the southern margin of the Sierra Pelona.

Mylonitic zones which may be extensions of the Vincent thrust are exposed in three other areas within the San Gabriel Mountains. Mylonitic rocks about 1000 feet thick are exposed in an area of about 2 square miles south of the San Gabriel fault in the central part of the range. These rocks are very similar to those of the Vincent thrust and would be very close to the exposed position of the thrust if the strike-slip displacement along the San Gabriel fault could be removed.

Several hundred feet of mylonitic rocks are exposed beneath anorthosite and related rocks in Mill Canyon in the western part of the range (Carter, 1971). The upper part of the mylonitic sequence is derived from anorthosite, but the lower part is derived from amphibolite and granodiorite which are different from any other rocks exposed in nearby areas. Thus it appears that the anorthosite complex is underlain by a major thrust fault, perhaps an upward arched segment of the Vincent thrust.

A thick sequence of rocks, mostly mylonite, crops out in a northward-dipping, east-striking belt near the southeast margin of the range east of the San Antonio fault. These rocks have been investigated by Alf (1948) and Hsu (1955), but their tectonic significance has not been determined. Several miles north, similar mylonites occur in the upper part of the thick sequence of southward-dipping mylonitic rocks along the Vincent thrust. In both areas, the mylonites cut Mesozoic granitic rocks and could be the same age. Perhaps the belt of mylonite near the southeastern margin of the range is the down-dip extension of the Vincent thrust which has been tilted and uplifted into its present position by Cenozoic deformation.

Geophysical studies might help to trace subsurface extent of the Vincent thrust and the thrust faults that produced the mylonite exposed in Mill Canyon and in the southeastern part of the range. Perhaps the igneous and metamorphic rocks that form the bulk of the exposures within the range terminate downward against a thrust fault. Significantly different rocks may be present at the depths where earthquakes originate.

Cenozoic Faults

The San Gabriel Mountains owe their bold southern front to Quaternary uplift along a system of reverse faults collectively referred to as the Sierra Madre fault system. In addition to these faults, several major high-angle faults transect the range without directly influencing the range's configuration. The most prominent include the San Gabriel, San Jacinto, and San Andreas faults, all of which strike between northwest and west and appear to have right-lateral displacements of many miles. Next in prominence are a number of northeast-striking faults which appear to have both vertical and left-slip along them. The most important of these are the Soledad fault along the northwest margin of the range and the San Antonio fault in the eastern part of the range.

Minor faults with displacements of a few inches to tens of feet are common throughout the range but appear to have little influence upon the distribution of rock units. Many result from slippage along preexisting joints and probably accommodate changes in shape brought about by distortion of the brittle rocks.

San Gabriel Fault

The San Gabriel fault enters the western San Gabriel Mountains east of Newhall and trends south 65 degrees east across the southwestern part of the range to Big Tujunga Canyon where it splits into a northern branch and a southern branch. The northern branch continues eastward for 12 miles along a trend of about south 70 degrees east and then bends nearly due east and extends across the center of the range to the community of Mount Baldy where it is truncated by the San Antonio fault. The trace of the northern branch is well marked by major canyons which have been eroded along it. The southern branch trends south 50 degrees east from Big Tujunga Canyon to the front of the range above Altadena where it bends eastward and becomes entwined with the system of frontal faults. It is generally believed to continue eastward along the range front, but perhaps it trends southeastward into the San Gabriel Valley concealed beneath a mantle of alluvium. The southern branch of the San Gabriel fault is frequently referred to as the Sierra Madre fault; however, as used here, the "Sierra Madre fault" refers exclusively to the system of reverse faults along the southern margin of the range.

Crowell (1952, 1962, 1968) has presented evidence indicating that the segment of the San Gabriel fault which extends northwestward from the San Gabriel Mountains has a total right-lateral displacement of about 30 miles, of which about 20 miles has occurred since late Miocene time. If the rocks were returned to their presumed original positions, gneiss similar in origin and history to the Mendenhall Gneiss, but presently exposed along the west side of the fault south of Gorman, would be placed next to the Mendenhall Gneiss in the southwest corner of the San Gabriel Mountains. This would rectify the existing mismatch of crystalline rocks across the San Gabriel fault in the western San Gabriel Mountains. As presently seen, Precambrian Mendenhall Gneiss on the north side of the fault is only mildly affected by Mesozoic metamorphism; whereas, Paleozoic(?) metasedimentary rocks on the south side are intricately intruded by Mesozoic granitic rocks and largely converted to gneiss and migmatite.

Within the central San Gabriel Mountains, the northern branch of the fault has a net right-slip of about 14 miles as shown by the offset of the vertical western margin of the Lowe Granodiorite. If the rocks along the north branch were returned to their prefault position, the south branch of the fault would split off very close to the 20-degree bend in the trace of the north branch and would be in alignment with the trace further west. This suggests that the bend in the north branch may be an original feature produced by the intersection of two faults.

West of where the San Gabriel fault splits into two branches, rocks on opposite sides of the fault are mismatched. Removal of 14 miles of right-slip along the north branch, so as to place rocks in their original position, fails to improve the match west of the split. Dip-slip faulting does not appear to provide a solution. The youngest terrane is on the south side of the fault, suggesting the south side has moved down relative to the north side. However, Mesozoic rocks imply the opposite sense of movement. Granitic rocks on the south side are coarser grained and more mafic than those on the north and have extensively migmatized the rocks they intrude, whereas those on the north have only mildly affected the rocks they intrude. Thus, strike-slip faulting appears to provide the most plausible explanation for the mismatch. If the net right-slip is about 30 miles (Crowell, 1968, p. 327), the net right-slip along the southern branch of the fault should be about 16 miles and rocks in the southwest corner of the range should have been adjacent to those along the southern branch of the fault prior to faulting. This would improve the match of Mesozoic granitic rocks, but the older rocks would still be mismatched. Perhaps the differences could be explained by dip-slip displacement with the south side down, or perhaps the right-slip along the southern branch of the fault is more than 16 miles.

The San Gabriel fault was nearly continuously active from late Oligocene to the Pleistocene as shown by data collected northwest of the range by Crowell (1952, 1962, 1968). Rocks within the San Gabriel Mountains provide limited data on the timing of displacements. The earliest faulting predated the intrusion of middle Miocene dikes in the central part of the range. The dikes are locally concentrated along the northern branch of the San Gabriel fault, and a few occur along the southern branch. Although the dikes are commonly disrupted by younger faulting, in some places they clearly intrude intensely sheared rocks, and baked fault gouge occurs locally along their margins.

In the western part of the range, Pliocene conglomerates south of the fault are displaced from their source areas north of the fault. Conglomerate at the top of the lower Pliocene marine section, which crops out west of the mouth of Big Tujunga Canyon, contains clasts of Lowe Granodiorite and cataclastic Mendenhall Gneiss similar to that exposed between Strawberry Peak and Devil's Canyon in the central part of the range. The conglomerate lacks clasts of anorthosite and Mendenhall Gneiss of the types which occur across the fault from the conglomerate's present position. A right-slip of 12 to 18 miles is indicated if sediment transport was from north to south. The displacement might be as little as 6 to 8 miles if sediment transport was more nearly east to west.

A sliver of fossiliferous Pliocene marine sandstone (Pml on the Geologic Map of California) occurs along the San Gabriel fault in Gold Canyon, 1½ miles west of Big Tujunga Canyon. A gravel lens within it is composed of pebbles and cobbles of Lowe Granodiorite. No clasts of anorthosite or Mendenhall Gneiss were observed. The closest possible source area is on the north side of the southern branch of the fault, 7 miles to the east. The furthest possible source area is more than 20 miles to the east. A right-slip of 7 miles would be the minimum displacement along the southern branch of the fault and would not include contemporaneous movement along the northern branch.

Middle-to-upper Pliocene marine conglomerate crops out east of Newhall, north and west of the entrance to Placerita Canyon State Park, and less than a mile south of the San Gabriel fault. The conglomerate contains small subangular clasts of Mendenhall Gneiss, anorthosite, and gabbro. The closest possible source is along the north side of the fault about 4 miles to the east, and the furthest possible source is about 12 miles to the east. The area directly across the fault is underlain by Miocene and Pliocene sedimentary rocks containing round clasts of many different rock types, thus precluding it as a source area.

Lower Pleistocene alluvial sediments of the Saugus Formation are faulted and strongly deformed where they occur along the south side of the San Gabriel fault in Little Tujunga Canyon, but there is little evidence for major strike-slip faulting.

There is no evidence for recent movement along the San Gabriel fault. Alluvial terrace deposits occur locally along the fault zone. None appear to be cut by faults.

San Jacinto Fault

The Glen Helen fault, within the San Jacinto fault zone enters the east end of the San Gabriel Mountains with a strike of about north 45 degrees west. It cuts across ridge spurs along the east side of Lytle Creek, gradually curving so as to strike about north 60 degrees west where it enters the canyon bottom near Glen Ranch. From there, the San Jacinto fault extends along the bottom of Lytle Creek to the drainage divide and thence along the bottom of Prairie Fork of the San Gabriel River to Vincent Gap where its strike is about north 65 degrees west. From Vincent Gap it continues westward across the drainage of Big Rock Creek for about 10 miles and then curves to within half a mile of the San Andreas fault; this segment of the San Jacinto fault is referred to as the Punchbowl fault on the Geologic Map of California. West of its convergence with the San Andreas fault, it is essentially part of the San Andreas fault zone, possibly representing the most southerly major break which is called the Nadeau fault.

Southeast of the San Gabriel Mountains, the San Jacinto fault has been very active in recent time as attested to by several historic earthquakes and abundant topographic evidence of surface faulting. Recent displacement has been primarily right-lateral. A total right-lateral displacement of about 15 miles has occurred along the fault within the Peninsular Ranges of southern California (Sharp, 1967, p. 717).

Within the San Gabriel Mountains, topography along the San Jacinto fault is erosional in origin. There is no obvious topographic evidence of recent displacement such as that seen along the San Andreas fault to the north. Perhaps recent displacements along the San Jacinto fault south of the range have been accommodated by movement along the San Andreas fault within the range.

A total right-slip of about 25 miles appears to have occurred along the San Jacinto fault within the San Gabriel Mountains. Dibblee (1967, p. 114) has correlated the fault separating Pelona Schist of Blue Ridge from granitic rocks of Pinyon Ridge in the northeastern part of the range with a similar fault along the north side of Sierra Pelona west of the range. My own studies indicate the Pelona Schist of Blue Ridge is similar to that of Sierra Pelona; and the Pelona Schist, Vincent-thrust rocks, and intrusions of quartz-monzonite porphyry exposed in the Crafton Hills east of Redlands are similar to those in the San Gabriel Mountains south of the San Jacinto fault (Ehlig, 1968, p. 301). The apparent difference in displacement within the San Gabriel Mountains as compared to that in the Peninsular Ranges may be accounted for by movement on the Banning fault or other faults within the San Andreas fault system.

San Andreas Fault

The San Andreas fault strikes north 64 degrees west in a nearly straight line along the northern edge of the San Gabriel Mountains. Offset drainage channels fault line troughs, sag ponds, pressure ridges, and scarps provide abundant evidence of recent movement. The principal component of Quaternary displacement is right-lateral. Vertical displacement is common but changes along the fault trace and lacks regional consistency. In fact, the San Andreas fault extends from low terrain in Cajon Pass to high terrain in the Wrightwood-Big Pines area and back down to low terrain near Valyermo without obviously influencing the broad-scale topography. This suggests (1) that the mechanism of range uplift is independent of the position of the San Andreas fault and (2) that uplift and erosion are rapid enough to mask the effect of lateral offset of topography by slippage along the San Andreas.

Evidence for displacement along the San Andreas fault has been reviewed by Crowell (1962). A net right-slip of 130 miles is suggested by the fact that the Orocopia Mountains (north of the San Andreas fault in southeastern California) contain rocks similar in origin, history, and age to those in the western San Gabriel Mountains south of the fault (Crowell and Walker, 1962; Silver, 1971). For the purposes of this report, it is important to note that crystalline rocks to the north of the San Andreas fault are unlike those to the south along the entire length of the San Gabriel Mountains.

Soledad Fault

The Soledad fault is traceable for a distance of about 10 miles along the north side of Soledad Canyon at the west end of the San Gabriel Mountains midway between the San Gabriel and San Andreas faults. It has an average trend of north 75 degrees east and dips steeply toward the north but is deformed and is offset by several younger faults (Oakeshott, 1958, p. 95; Carter and Silver, 1971). Major dip-slip displacement occurred along it between late Eocene and early Miocene allowing several thousand feet of volcanic and clastic sedimentary rocks of the Vasquez Formation to accumulate in the Soledad Basin north of the fault synchronous with uplift and erosion of plutonic rocks to the south (Jahns and Muehlberger, 1954). Movement along the Soledad fault ceased around mid-Miocene time. During the upper Miocene, the Mint Canyon Formation was deposited on top of the Soledad fault, thus concealing it. Erosion combined with regional tilting toward the west has exposed the Soledad fault eastward from the base of the Mint Canyon Formation. Near its easternmost exposure, plutonic rocks crop out on both sides of the fault. Further to the east, the Soledad fault is concealed beneath alluvium in Soledad Canyon and its exact position has not been determined.

The Soledad fault is ofen selected as the northwestern boundary of the San Gabriel Mountains. This is an arbitrary choice in that there has been no fault movement during the major epoch of range uplift. Differences in topography across it are the result of differential erosion. Where plutonic rocks crop out on both sides, there is little contrast in topography across it.

San Antonio Fault

The San Antonia fault extends northeastward along San Antonio Canyon (Wash) in the eastern part of the range. It is truncated by the San Jacinto fault on the north and appears to curve westward and form part of the frontal fault system on the south. Rocks of different origin and history are juxtaposed along all but the northern part of its trace where there is Pelona Schist on both sides. The granitic-gneissic complex of the central San Gabriel Mountains is exposed on the west side. The northern part of the complex has been mylonitized and partially recrystallized where it overlies Pelona Schist along the Vincent thrust fault. The complex probably represents Precambrian crust modified by Mesozoic intrusion and metamorphism.

The area east of the San Antonio fault is underlain by Paleozoic(?) metasedimentary rocks intruded and metamorphosed by Mesozoic granitic rocks. A belt of cataclastic rocks and mylonite, several thousand feet thick, extends nearly due east cross this terrane in the southern part of the range. Rocks south of the mylonite belt have, in part, undergone granulite-facies metamorphism, whereas those to the north are entirely of amphibolite facies. In the northern part of the area, several thousand feet of mylonitic rocks overlie the Pelona Schist along the Vincent thrust fault.

Relationships along the San Antonio fault appear to require a large strike-slip displacement. Simple dip-slip displacement can be ruled out because of the following relationships:

1. The northern branch of the San Gabriel fault, which is essentially vertical and has about 14 miles of right-slip along it, is truncated along the west side of the San Antonio fault. The nearest fault on the east side is in Icehouse Canyon 2 miles north. Rocks along this Icehouse Canyon fault are different from those along the San Gabriel fault.

2. Although the Vincent thrust fault is exposed on both sides of the San Antonio fault, mylonitic rocks on the east side are several times thicker than those on the west and contain rocks of metasedimentary origin whereas those to the west do not. Thus the two mylonitic sequences could not have fotmed side by side.

3. The mylonite belt which occurs on the east side near the front of the range has no counterpart on the west side.

About 3 miles of left-slip appears to have occurred along a branch of the San Antonio fault. a sequence of metasedimentary rocks is exposed in Evey Canyon between two branches of the San Antonio fault near the front of the range. What appears to be the same sequence of rocks is exposed to the east of the fault near Cascade Canyon, 3 miles to the north. In both areas, the rocks dip steeply toward the north and strike nearly perpendicular to the San Antonio fault.

Sierra Madre Fault System

The Sierra Madre fault system, as referred to here, includes all faults along the southern front of the San Gabriel Mountains that have participated in the Quaternary uplift of the range. The fault system is significantly more complex than is suggested by the relatively simple, bold southern face of the range. It appears to be broken into five or six segments, each 10 to 15 miles long and composed of numerous individual faults. Several of the faults curve into the range even though the continuity of topography within the range indicates the entire range has been uplifted essentially as a single block. The complexity appears to be due to a combination of four factors: (1) control of frontal faults by pre-existing faults, (2) restriction of movement to a single segment during each individual earthquake, (3) splaying of the movement-zone as it approaches the surface, and (4) deformation or rotation of fault surfaces into orientations unfavorable for recurrent movement. Limited exposures indicate that the frontal faults generally dip 30 to 70 degrees northward under the range.

The San Fernando earthquake resulted from movement along the San Fernando-Sunland segment of the Sierra Madre fault system. This segment is about 12 miles long, extending from Big Tujunga Canyon on the east to the join between the San Gabriel Mountains and the Santa Susana Mountains on the west. The earthquake was initiated by sudden slippage at a depth of 8 miles beneath a point 2½ miles northeast of the trace of the San Gabriel fault and directly beneath the surface contact between the crystalline rocks and sedimentary rocks of the Soledad Basin. From there, the slippage propagated southward and upward along a surface inclined at about 45 degrees and striking west-northwest (Allen, Hanks, and Whitcomb, this bulletin). Faulting broke the ground surface along the south limb of the Little Tujunga syncline. Details of surface faulting and geology are presented by Kahle *et al.* plates 2 and 3. In general, the near-surface movement followed a young fault zone that developed parallel to bedding in the underlying sedimentary rocks. The surface displacement includes both reverse-slip with the north side up and left-slip.

The earthquake caused no movement along the prominent fault zone separating exposed basement rocks from sedimentary rocks along the northern limb of the Little Tujunga syncline. As I interpret the geology, reverse faulting began along the range front during Pliocene-Pleistocene time and was accompanied by downfolding of the Little Tujunga syncline along the fault's leading edge. As a result of the faulting, the prism of basement rock exposed between the San Gabriel fault and the Little Tujunga syncline was detached from its roots. As reverse faulting continued at depth, near-surface crustal shortening was assimilated by synclinal folding of the sedimentary rocks and backward rotation of the detached prism of basement rock. In relatively recent time, the Little Tujunga syncline has become tight and more resistant to folding. As a result, the reverse faulting has extended across the axial surface of the syncline and has propagated upward along bedding planes within the southern limb of the syncline.

The eastern and western limits of faulting during the San Fernando earthquake coincide with discontinuities in the pattern of frontal faults. The eastern limit is along the bottom of Big Tujunga Canyon. As the frontal faults approach the mouth of the canyon from either side, they curve back into the range. Bedding within sedimentary rocks adjoining the faults has been upturned so as to strike parallel to the faults. As a result, sedimentary rocks on opposite sides of the canyon strike nearly at right angles to each other. Although the western limit of faulting is not marked by surface ruptures, a linear array of aftershocks (Allen and others, 1971) occurred along the zone of deformation and tear faults developed, separating the structures of the southwestern San Gabriel Mountains from the thrust faults and folds of the Santa Susana Mountains to the west. This suggests that the San Fernando-Sunland segment of the frontal fault system is a structural unit and that earthquakes produced by its displacement are triggered at different times than earthquakes produced by displacements along adjoining segments of the frontal fault system.

The segment of the Sierra Madre fault system extending from Big Tujunga Canyon eastward 10 miles to where the south branch of the San Gabriel fault emerges from the range appears to constitute a single unit. Although the faults are concealed by alluvium in most places along this segment, the nearly linear range front suggests that the faults are nearly straight, with an average strike of about north 60 degrees west. Both ends of the segment curve inward toward the range.

The central part of the Sierra Madre fault system is complicated by several faults which curve into the range. The most westerly is the south branch of the San Gabriel fault. It is commonly referred to as the "Sierra Madre fault"; but, as previously indicated, it is a nearly vertical strike-slip fault which shows no evidence of recent displacement. About 10 miles further east, the frontal faults appear to curve northeastward into the range and join the Sawpit Canyon fault. The picture is further complicated by the Raymond Hill fault which joins the range front a mile south of the Sawpit Canyon fault and trends west-southwestward across the northwestern San Gabriel Valley. It produces a very prominent scarp in alluvium with the north side up. Further east along the range front, faults curve northeastward up Big Dalton and San Dimas Canyons. The details of the frontal fault system are fairly well known in this area as a result of investigations by the Metropolitan Water District of Southern California (Proctor, Payne, and Kalin, 1970).

North of Pomona, the range front jogs northeastward 4 miles to the mouth of San Antonio Canyon. Although the frontal fault is not exposed in this area, the jog is in alignment with a branch of the San Antonio fault which extends north-northeastward across the interior of the range.

To the east of San Antonio Canyon, the frontal faults extend about north 85 degrees east for 14 miles to the San Jacinto fault at the east end of the range. This segment of the Sierra Madre fault system appears to move as a unit and is referred to as the Cucamonga fault zone. It is marked by young fault scarps described by Eckis (1928).

Much more must be learned about the Sierra Madre fault system before we will be able to predict the location of future fault displacements and thereby prevent damage such as occurred during the San Fernando earthquake. Unfortunately, poor exposures limit the amount of data that can be gathered from surface observations.

AGE AND MECHANISM OF RANGE UPLIFT

How long have the San Gabriel Mountains existed as a mountain range? One might answer that part of the range dates back to at least Oligocene. Mountains occupying the same area as the northwestern part of the modern range shed sediments westward and northward into the Soledad basin almost continuously from Oligocene to present. However, the pre-Pleistocene physiography was quite different from that of today. For example, Pliocene marine rocks occur in the southwestern part of the range, and Miocene marine rocks occur along the southwestern and south-central range margins. Alluvial deposits of Miocene and Pliocene age exposed along the northeastern margin of the range were derived from the Mojave Desert region to the north and northeast and show no evidence of a mountain range to the south. Also, reconstruction of displacements along the San Gabriel, San Jacinto, and San Andreas faults indicate that currently adjacent rocks were many miles apart in mid-Cenozoic time. Thus it is inappropriate to correlate precisely pre-Pleistocene mountains with the modern range.

As best as can be determined, the San Gabriel Mountains proper began to acquire their modern configuration during the early Pleistocene but did not acquire their present height until late Pleistocene and Holocene time. Uplift of the eastern half of the range is recorded by a reversal in the source direction of alluvial deposits along the northeastern range margin. Whereas the Miocene and Pliocene deposits came from the Mojave Desert and contain no clast types characteristic of the San Gabriel Mountain basement terrane, Pleistocene gravels came from the south and contain abundant clasts of Lowe Granodiorite, Pelona Schist, and other rock types characteristic of a San Gabriel Mountain source. Although the western part of the range north of the San Gabriel fault has been a positive area since at least the Oligocene epoch, the area south of the San Gabriel fault was below sea level as recently as the Pliocene and was the site of thick accumulations of alluvium during early Pleistocene time.

There are remnants of a subdued erosion-surface and alluvial terrace deposits in many places, particularly near the range margins and along the sides of major drainage systems. They indicate that the San Gabriel Mountains were quite low in mid-Pleistocene time, with broad valleys extending into the interior of the range. Late Pleistocene and Holocene uplift has resulted in rapid down-cutting of major drainage channels and has produced steep-sided V-shaped canyons. Less uplift has occurred in the western part of the range than the eastern part.

Why have the San Gabriel Mountains been uplifted, and what controls their size and shape? The answer cannot be obtained from the rocks exposed within the range. Whereas the range's internal geology is very complex because of multiple stages of metamorphism, intrusion, and faulting, range uplift has followed a relatively simple pattern of reverse faulting along the southern margin and broad arching along the northern margin. Furthermore, rather than being an isolated range, the San Gabriel Mountains are part of a continuous chain of mountains within the Transverse Range province of southern California. The San Bernardino Mountains are directly east of them across the San Andreas fault. The two ranges are separated by Cajon Canyon which has formed by erosion of sheared basement rock and Tertiary strata along and adjacent to the San Andreas fault. Pleistocene alluvial deposits form bluffs interconnecting the two ranges north of Cajon Canyon. The deposits have been tilted northward toward the Mojave Desert along their entire exposed length of 27 miles. Bedding dips 10 to 25 degrees north in the lower part of the deposits and 5 to 15 degrees north in the upper part.

The Santa Susana Mountains are a westward extension of the San Gabriel Mountains. They are underlain by several thousand feet of Cenozoic strata, mostly of marine origin. As recently as lower Pliocene, ocean depths of 2000 to 3000 feet are believed to have existed in the central part of the range (Winterer and Durham, 1962, p. 314). Lower Pleistocene alluvial deposits which are folded into a tight syncline along the southern margin of the Santa Susana Mountains contain clasts of schist derived from Sierra Pelona, 15 miles to the northeast at its closest point. The deposits contain all other clast types found in the Soledad Basin and adjacent basement terrane north of the San Gabriel fault. Apparently, an alluvial slope drained southward across the Soledad basin and Santa Susana Mountains to a trough along the northern edge of the San Fernando Valley in lower Pleistocene time. Thus, uplift of the Santa Susana Mountains has occurred during the late Pleistocene and Holocene. Unlike the San Gabriel Mountains, uplift was accomplished by tight folding in combination with thrust faulting; however, this difference in style of deformation is due to the presence of a thick sequence of thin-bedded sedimentary rocks.

In conclusion, the San Gabriel Mountains are a segment of the much larger Transverse Ranges province, and their uplift is apparently due to the same causes as those that have produced the Transverse Ranges. The Transverse Ranges form a roughly wedge-shaped province that opens westward with an apical angle of about 15 degrees. The present ranges have been formed by Pleistocene and Holocene crustal shortening along a north-south axis. It is commonly assumed that the shortening has been caused by redirection of strike-slip movement along the bend in the San Andreas fault. Another possibility is that sea-floor spreading is occurring more rapidly in the southern part of the Gulf of California than the northern part. This would result in a clockwise rotation of Baja California and southern California southward from the San Andreas fault and could produce the Transverse Ranges by a nutcracker-like lever action. Whichever may be the cause of the crustal shortening, the basement rocks of the San Gabriel Mountains are deforming as a competent, semirigid unit with brittle rupture along the south side and arching on the north side. The San Fernando earthquake provides proof that range uplift is still going on and that earthquakes are likely to occur along other segments of the range front within the foreseeable future.

CHAPTER 3

Geology of the Epicentral Area[1]

by Gordon B. Oakeshott [2]

The pattern of principal ground rupturing, landsliding, and ground shaking in the San Fernando earthquake and its aftershocks consists of a roughly triangular area about 20 km on a side, although some landsliding took place over 30 km from the epicenter. The epicenter of the main shock is about the apex of this triangle; the aftershock pattern approximates the eastern and western sides; and the irregular, discontinuous surface ruptures in the fault zone make a base to the triangle about 15 km long.

The fault break that caused the earthquake originated at a hypocenter about 8 km deep in the crystalline rocks, 13 km north-northeast of San Fernando, and progressed upward toward the south at an average rate of about 2½ km per second (Allen, this Bulletin; and Bolt, this Bulletin). Maximum deformation was elevation of the mountain block about 2 m and shift of that block westward (left-lateral slip) by 2 m. The San Fernando Valley block, south of the fault trace, showed little or no movement. Amount of crustal shortening along a N 20° E line was on the order of 2 m.

The complex 1971 San Fernando fault trace at the foot of the mountains on the sloping floor of the San Fernando Valley is irregular and discontinuous, and the strike of the trace changes from N 70° W in the Lakeview-Tujunga segment through due W in the Sylmar segment to SW in the Santa Susana fault zone. At the ground surface, dip and net slip of the fault vary within wide limits along the strike. Seismological data show that the initial fault rupture at the hypocenter was on a fault surface dipping 50° N and that the average dip of the fault surface was about

[1] In part from Oakeshott (1958). Manuscript submitted for publication June 1972.

[2] At time of earthquake, Deputy Chief, California Division of Mines and Geology, Sacramento. Now Special Lecturer, California State University, Sacramento, and Consultant.

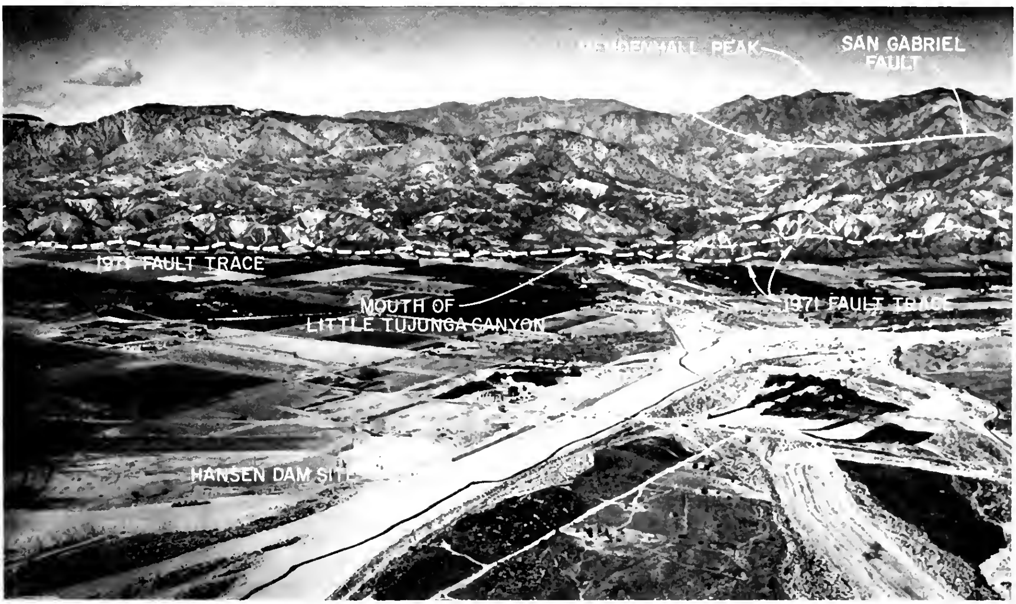


Photo 1. Looking north across Tujunga Wash in 1938. Construction of Hansen Dam for flood control had begun. Little Tujunga Canyon heads in a broad depression in the summit ridge of the San Gabriel Mountains on the skyline. Mendenhall Peak is 4582 feet high. North-dipping strata of the Modelo Formation form the lowest part of the range visible in the photograph. The irregular, interrupted trace of the 1971 fault lies close to the junction of the mountain range and the San Fernando Valley. *Photo by Spence Air Photos.*

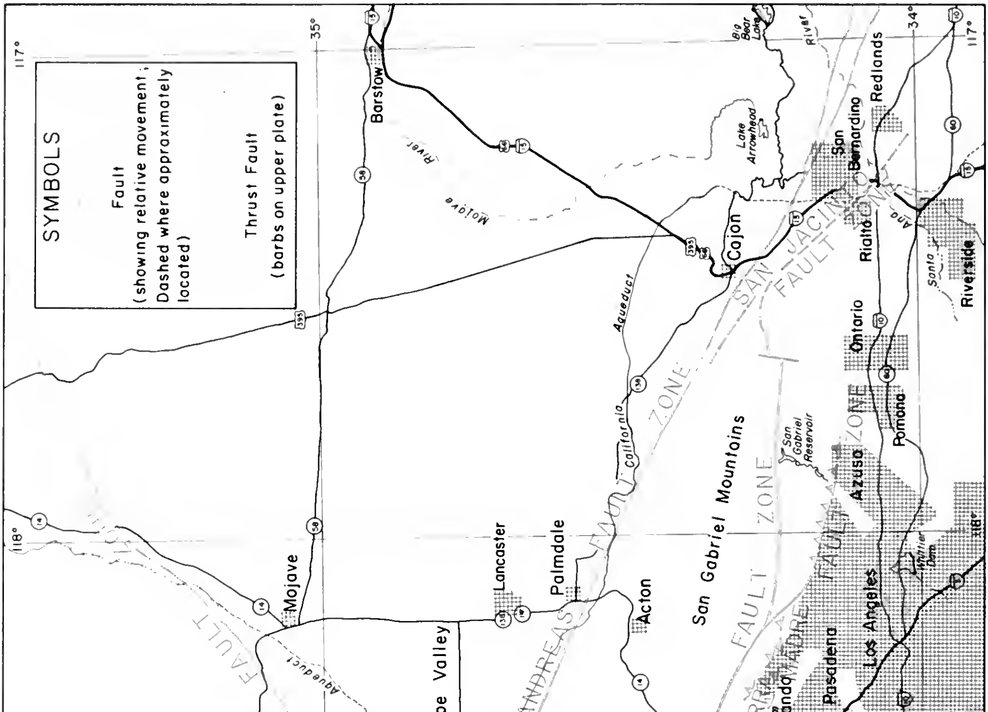


Figure 1. Index map of a part of southern California showing San Fernando earthquake area and major faults.

Photo 2. The 1971 fault scarp within the Modelo Formation in lower Lopez Canyon. This is not the main San Fernando fault trace but is a short, associated bedding-plane fault called the Oak Hill fault (Kamb *et al.*, 1971; Proctor *et al.*, 1972). The visible dip of the fault plane is north, parallel to the dipping thin sandstone beds of the Modelo outcrop on the upthrown side. Height of the fault scarp is close to 3 feet.

35° (Bolt, this Bulletin). Surface mapping by the Division of Mines and Geology (Barrows, Kahle, Weber, and others in this Bulletin) and borehole data from the Metropolitan Water District suggest that these attitudes flatten until many near-surface fault dips are 20° or less.

THE CRYSTALLINE ROCKS

The "core" (which may well be cut off by thrust faulting of large displacement at depth) of the western San Gabriel Mountains consists of coarse-grained crystalline rocks of great variety which range in age from Precambrian to Late Cretaceous. The mountains are flanked on three sides by sedimentary strata derived from the crystalline rocks and representing all epochs of the Tertiary and Quaternary periods.

The oldest known rock unit in the western San Gabriel Mountains is the Precambrian Mendenhall Gneiss, a retrograded, charnockitic granulite of obscure origin whose blue-quartz-feldspar gneiss, amphibolite, and biotite-hornblende gneiss may represent rocks of sedimentary, volcanic, and plutonic origin. These rocks crop out over 9 square miles in a belt just north of the San Gabriel fault and are shown in the geologic map (plate 1). The anorthosite-gabbro group of rocks, also of Precambrian age, which crops out over 80 square miles of the western San Gabriel Mountains, has intruded the Mendenhall Gneiss. Radiometric age of the anorthosite and related rocks is 1.22 billion years; lead-zinc age for the Mendenhall Gneiss is 1.44 billion years (Silver, *et al.*, 1963). Principal rock types in the San Gabriel anorthosite-gabbro complex are andesine anorthosite, gabbroic anorthosite, anorthositic gabbro, metagabbro, metanorite, diorite and metadiorite, metapyroxenite, titanomagnetite rocks, a minor amount of olivine gabbro, hornblende norite, hornblende gabbro, and small bodies of gabbro pegmatite. These rocks are all facies of the anorthosite-gabbro group of nearly the same age. Certain facies overlapped in time of formation, and contacts may be sharp or gradational.

The outcrop of the anorthosite body is oval in plan, the long axis trending N 70° W for 19 miles north of and parallel to the San Gabriel fault; the body's depth and what underlies it are unknown. Internal structural features, including bordering platy flow banding, discontinuous fractures and granulation, mafic tabular bodies, block structure, and micro-shattering of pyroxene and plagioclase crystals, are features which developed in the body of gabbroic-anorthosite magma while it crystallized slowly, under pressure, from its outer to its inner portions. Contacts of the anorthosite group with the older gneisses are essentially concordant, but local discordant relationships with Mendenhall Gneiss occur.

If the depth of hypocenter of the main shock of February 9 was truly about 8 km, then the initial fault

Photo 3. White Precambrian anorthosite exposed in Soledad Canyon, about 3 miles northeast of the earthquake epicenter. *Photo by Southern Pacific Company.*

break probably took place in the Precambrian rocks.

Three major groups of rocks of uncertain age probably represent parts of the very long period of time from Late Precambrian to Late Cretaceous. They are the Pelona Schist, Placerita Formation and the "diorite gneiss" (Geologic column, figure 2). The mica-chlorite-albite schist, actinolite-albite schist, quartz-biotite schist, quartzite, and actinolite-talc schist of the Pelona are regionally metamorphosed fine-grained sedimentary and volcanic rocks which do not appear in the epicentral area proper (See Ehlig, this Bulletin) but appear in a large block a few miles north of the epicenter.

The Placerita Formation consists of metamorphosed sedimentary rocks that appear as roof pendants in Late Cretaceous granitic rocks, south of the San Gabriel fault. Rock types include crystalline limestone and dolomite, graphitic schists, and feldspathic gneiss that closely resemble the Mississippian Furnace limestone and metasedimentary rocks of the San Bernardino Mountains in many respects; their correlation is suggested. The Placerita metasedimentary rocks are intimately associated with dark dioritic gneiss, migmatites, and biotite schist mapped collectively as "diorite gneiss". The latter may well correlate with the border facies of the Lowe Granodiorite (Ehlig, this Bulletin), age 220 ± 10 million years (Permian-Triassic).

Granodiorite, quartz monzonite, granite, and other granitic rocks exposed in about 30 square miles of the epicentral area probably correlate with similar plutonic rocks in the Transverse and Peninsular Ranges, the Mojave Desert, and southern Sierra Nevada, which are of Late Cretaceous age. A few radiometric dates on the order of 70 million years in the San Gabriel Mountains have been obtained. It is probable that an ancestral San Gabriel Mountain range was built in Cretaceous time. This range was eroded to a low level by the close of the Cretaceous and Paleocene seas transgressed the site.

THE SEDIMENTARY ROCK FORMATIONS

The topographic and structural high of the Cenozoic San Gabriel Mountains, probably in existence continuously during post-Paleocene time, furnished sediments to form the many thousands of feet of Cenozoic marine and continental sedimentary formations, with intercalated volcanic rocks, which flank the western end of the mountains on three sides. The San Gabriel fault divides the eastern Ventura basin

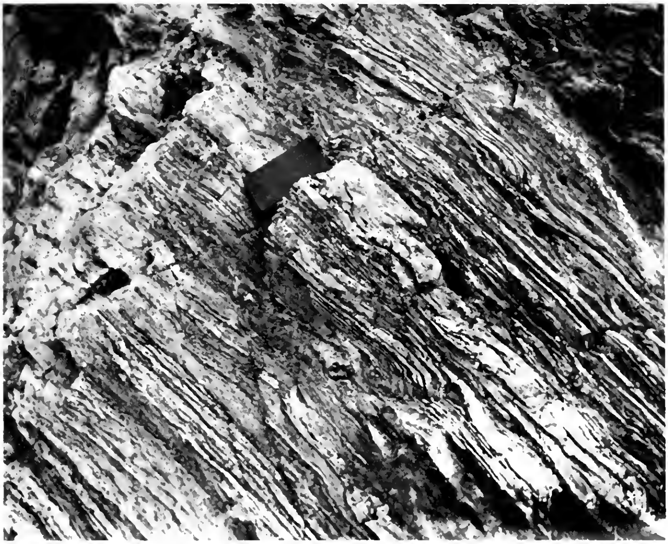


Photo 4. Pelona Schist in Bouquet Canyon about 8 miles northwest of the epicenter of the earthquake. *Photo by Mary Hill.*

into two local provinces of quite different geologic history: the Soledad basin northeast of the fault and the San Fernando basin south of the fault.

In the Soledad basin, late Eocene to late Miocene time is represented by an aggregate thickness of nearly 14,000 feet of nonmarine fluviatile and lacustrine sediments and interbedded volcanic rocks comprising the Vasquez, Tick Canyon, and Mint Canyon formations. The three formations have unconformable relationships, and none has been recognized southwest of the fault. The Modelo Formation of the Mohnian-Delmontian foraminiferal stages unconformably overlies the Mint Canyon Formation.

In the San Fernando basin, middle Eocene marine beds of the Domengine Formation crop out in Elsmere Canyon, and wells in the area have penetrated marine beds of the Meganos, Capay, and Domengine stages of late Paleocene to middle Eocene age. The middle Miocene nonmarine sandstone, conglomerate, and volcanic flows of the Topanga(?) Formation underlie at least 3000 feet of marine beds of the Modelo Formation of the Luisian and Mohnian stages of middle and upper Miocene. The marine Paleocene "Martinez" Formation crops out only as slivers in the San Gabriel fault zone. Thus, the Soledad and San Fernando basins were probably first developed in late

Photo 5. Looking east at Mendenhall Peak (Lookout) from upper Limekiln Canyon. Lower Pleistocene Saugus Formation in foreground capped by terrace gravels, separated from granitic rocks by the De Mille branch of the San Gabriel fault. High on the mountain slope, the San Gabriel fault is the contact between Cretaceous granitic rocks (prominent white outcrops center to right) and the Precambrian Mendenhall Gneiss which forms the ridgecrest. *Charles W. Chesterman photo.*

GENERALIZED GEOLOGIC COLUMN
SAN FERNANDO EARTHQUAKE AREA

	AGE	FORMATION OR MEMBER	MAXIMUM THICKNESS (FEET)	DESCRIPTION
QUATERNARY	RECENT	Alluvium	1,000 +	Coarse sand, gravel, and boulders of San Fernando and Tujunga valleys.
QUATERNARY	UPPER PLEISTOCENE	Terroce deposits	200	Fanglomerate, stream terrace gravels, and older alluvium.
QUATERNARY	MIDDLE PLEISTOCENE	Pacoima Fm	1,000	Brown-reddish-brown, poorly sorted conglomerate and fanglomerate; folded.
QUATERNARY	LOWER PLEISTOCENE	Sougus Fm	6,400	Light-colored, poorly sorted, loosely consolidated nonmarine conglomerate and coarse sandstone, fluviatile and alluvial-fan deposits.
TERTIARY	UPPER PLIOCENE	Pico Formation: Upper Pico Mbr	(Upper Pico 300 ?)	Nonmarine fluviatile, lacustrine, and brackish-water gray gravel, greenish gray sandstone, sandy mudstone, conglomerate and thin freshwater limestone beds of Sunshine Ranch gradational, in part, into marine sandstone of Upper Pico Member in Placerita area and west of San Fernando Reservoir.
TERTIARY	UPPER PLIOCENE	Pico Formation: Sunshine Ranch Mbr	3,000	
TERTIARY	MIDDLE PLIOCENE	Pico Formation: Lower Pico Mbr	700	Marine brownish sandstone, siltstone, and conglomerate, fossiliferous calcareous sandstone beds.
TERTIARY	LOWER PLIOCENE	Repetto Fm: Repetto Fm undiff	3,000	Marine coarse sandstone and conglomerate, sandy shale, laminated gray and brown shaly sandstone, massive chocolate brown siltstone with carbon fragments, yellow jarosite(?) and gypsum.
TERTIARY	LOWER PLIOCENE	Repetto Fm: Elsmere Mbr	(Elsmere 1,400)	Marine conglomerate, gray and brown sandstone, massive gray and chocolate brown siltstone, silty shale and white arkose, base oil-saturated in Elsmere Canyon area.
TERTIARY	UPPER TO MIDDLE MIOCENE	Modelo Fm	3,000	Marine fine to coarse arkosic sandstone and conglomerate, thinly bedded siliceous, calcareous, silty, and diatomaceous shale.
TERTIARY	MIDDLE (?) TO LOWER (?) MIOCENE	Topanga (?) Fm	1,000	Coarse reddish and yellowish arkosic sandstone, mudstone, conglomerate and a large proportion of vesicular basaltic flows and reddish purple breccia, mostly nearshore nonmarine but top 200 feet marine in Pacoima Hills.
TERTIARY	MIDDLE EOCENE	Domengine Fm	650	Marine greenish gray calcareous sandstone, coarse brown sandstone, and cobble conglomerate.
TERTIARY	LOWER EOCENE TO PALEOCENE	(Capay stage)	?	Subsurface in Whitney Canyon area.
TERTIARY	LOWER EOCENE TO PALEOCENE	(Meganos stage)	?	Subsurface in Whitney Canyon area.
TERTIARY	PALEOCENE	"Martinez" Fm.	1,500 +	Marine dark greenish black to olive gray sandstone, thin interbeds of black shale. Thick massive well-cemented lenticular beds of pebble conglomerate. In San Gabriel fault zone.
LATE PALEOZOIC TO LATE CRETACEOUS		Placerita and Diorite gneiss Fms and intrusive granitic rocks	(Placerita 2,000+)	**South of San Gabriel Fault** Crystalline limestone and dolomite, graphite and biotite schist, and quartzite of the Placerite Formation (pm), associated with and intruded by dark quartz diorite gneiss, migmatites, and biotite schist (dgn), all intruded by Late Cretaceous granitic rocks (gr).
PRE-CAMBRIAN		Mendenhall Gneiss and anorthosite-gabbro group		**North of San Gabriel Fault** Mendenhall blue-quartz-feldspar gneiss (pCm) intruded by anorthosite-gabbro rocks (an), all intruded by Late Cretaceous granitic rocks (gr).

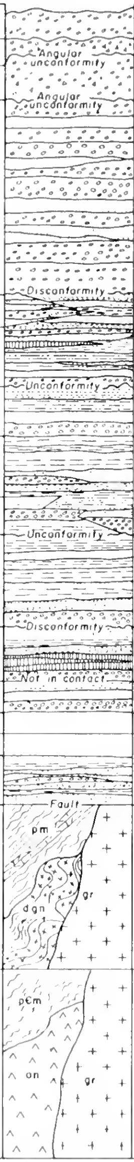


Figure 2. Geologic column, western San Gabriel Mountains.

Photo 6. Contorted thin-bedded sandstone of the upper Miocene Madelo Formation. White sandstone bed is about one foot thick. *Charles W. Chesterman photo.*

Eocene time as the western San Gabriel Mountains rose. Paleocene seas were the last to cross the San Gabriel Mountain area.

Pliocene time is represented by marine rocks of the lower Pliocene Repetto Formation and middle and upper Pliocene Pico Formation, south of the San Gabriel fault. The marine Pliocene has a maximum thickness of about 4000 feet in San Fernando basin, in contrast to not more than 200 feet in Soledad basin. The nonmarine and brackish-water upper Pliocene Sunshine Ranch Member of the Pico Formation has a thickness of 3000 feet at Van Norman Reservoir and a maximum thickness of 1300 feet in Soledad basin. The term "Towsley Formation" (Winterer and Durham, 1962) used in some papers in this Bulletin may include some late Miocene and early Pliocene units as used in this paper.

The continental lower Pleistocene Saugus Formation is widely distributed both north and south of San Gabriel fault; maximum thickness is 6400 feet in San Fernando basin but only 650 feet in Soledad basin. Reddish fanglomerate of the middle(?) Pleistocene Pacoima Formation unconformably overlies the Saugus Formation in the northwestern part of the San Fernando basin. Upper Pleistocene terrace deposits of several ages are widely distributed and flatly

Photo 7. Flat-lying Late Quaternary terrace gravel lying unconformably on tilted beds of the lower Pleistocene Saugus Formation. Steep slope at extreme upper right is underlain by Cretaceous granodiorite. The brush-covered strip hides the Lopez reverse-fault contact.

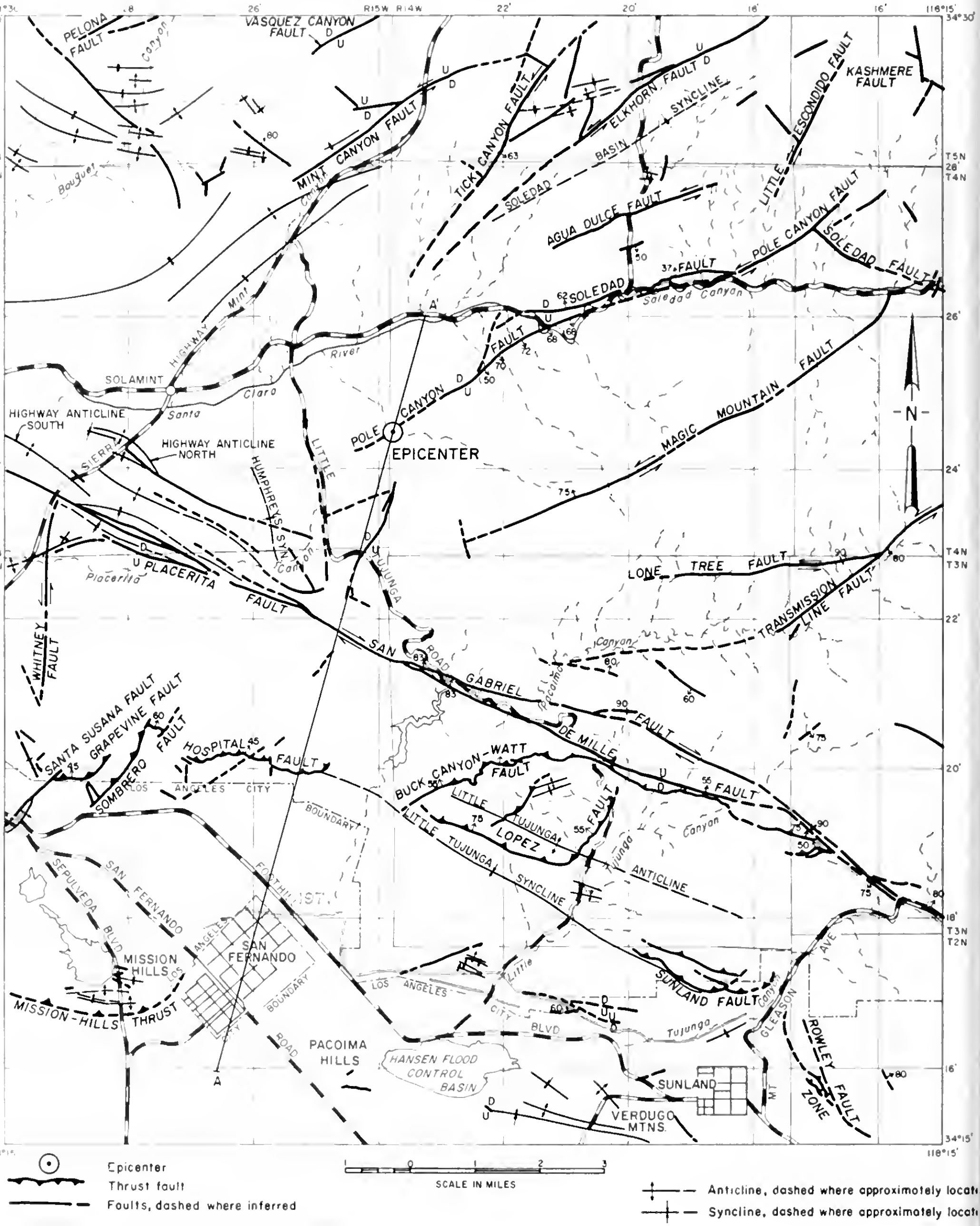


Figure 3. Geologic structure map of epicentral area, showing faults and folds.

overlie Pacoima, Saugus, and older formations.

Lithology, thickness, and description of the rock units in the epicentral area appear in the "Generalized geologic column" (figure 2).

STRUCTURAL PROVINCES AND HISTORY

Cenozoic structural history of San Fernando area involves three geologic provinces: the western end of the San Gabriel Mountain block of pre-Tertiary crystalline rocks, the Soledad basin of nonmarine Tertiary-Quaternary sedimentary rocks at the northeastern end of the Ventura basin, and the San Fernando basin of marine Tertiary-nonmarine Quaternary sedimentary rocks at the southeastern end of the Ventura basin, marginal to the Los Angeles basin. The Cenozoic record shows that intermittent, frequent uplift of the San Gabriel mountain block has taken place, accelerated at times, with faulting, folding, and readjustments around the margins of that competent crystalline block. Major northwest-trending and northeast-trending faults slice across crystalline-rock and sedimentary provinces and obliquely across the prevailing east-west trend of the San Gabriel Mountains. A major zone of reverse faults separates the crystalline block from flanking Cenozoic stratified rocks along the south side of the range, but some of the individual faults in this zone are within the sedimentary units or within the crystalline-rock units.

Structure of the area is dominated by the San Gabriel fault, which extends obliquely across the western San Gabriel Mountains. The pattern of faulting consists of: 1) a principal series of north-dipping shear planes along the San Gabriel fault zone trending N 65° W and showing right-lateral movement; 2) in the north block, a series of complementary left-lateral faults trending predominently N 65° E; and 3) in the south block, the series of north-dipping reverse faults of the Sierra Madre fault zone.

Right-lateral strike-slip movement on the San Gabriel fault has probably been on the order of 4 miles in Quaternary time, judging by displacement of older faults and sediments that lie on the crystalline rocks. Profound differences in rock types and in geologic history of the terrane north of the San Gabriel fault and that to the south indicate the importance of that fault zone. The Placerita fault is a major local branch of the San Gabriel fault. A sliver of late Pliocene beds of the Pico Formation some 1300 feet wide represents a synclinal downdropped block within the San Gabriel fault zone. This would require an apparent 1000-foot post-Saugus (post-early Pleistocene) component of displacement on the Placerita fault, in which relative movement was down on the north side. On the south plane of the San Gabriel fault nearby, there is an apparent vertical component of displacement of 700 feet up on the north side. At Sierra Highway, the most reasonable section that can be drawn shows the north block of the San Gabriel fault to have been raised a minimum of 1500 feet in post-Pacoima (mid-Pleistocene) time. Initial movements in the San Gabriel fault zone may have taken place as early as the time of the Late Cretaceous

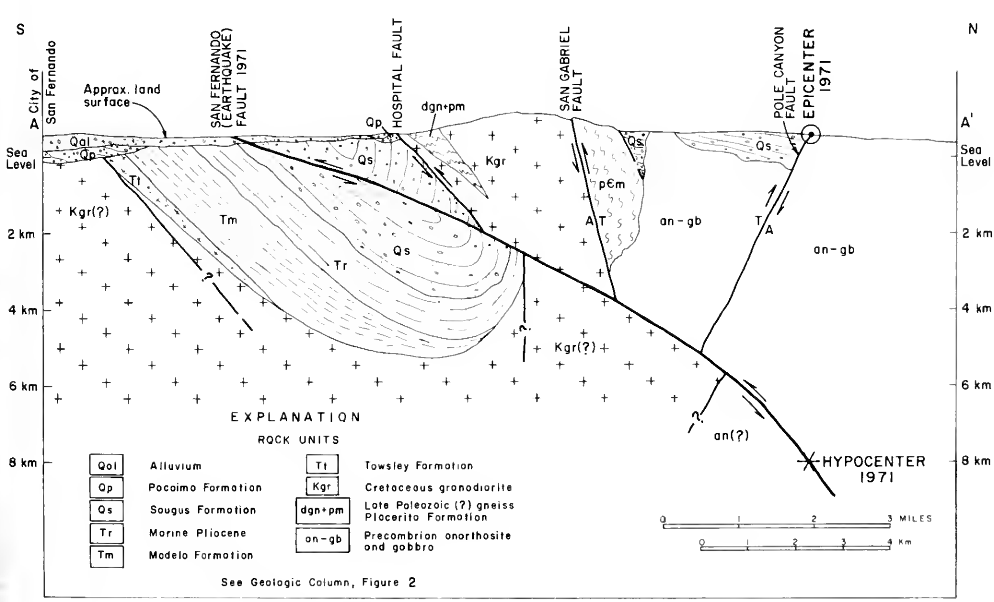


Figure 4. Geologic structure section through the earthquake hypocenter.

orogeny, but there is no positive evidence to indicate movement on this fault in latest Quaternary time. Subsequent fault activity may well have transferred to the San Andreas fault about 20 miles to the northeast.

The principal faults north of the San Gabriel fault zone are northeast-trending and have a large component of left-lateral horizontal displacement and a significant vertical component. They range in time of latest movement from pre-Miocene to Late Quaternary. The Soledad fault is a normal dip-slip fault that parallels Soledad Canyon and separates the Tertiary Mint Canyon and Vasquez formations of the Soledad basin from Precambrian anorthosite of the San Gabriel massif. It has probably defined this margin of the basin since late Eocene or early Oligocene time.

The dominant fold-structure of the southern sedimentary area, or San Fernando basin, is the asymmetrical Little Tujunga syncline, which changes its west-to-east trend from N 60° E parallel to the Santa Susana fault zone through due E and S 70° E parallel to the faulting of the Sierra Madre fault zone. North limb of the syncline is very steep to overturned and is partly cut out by the Sierra Madre faults.

Unconformities between the successive Cenozoic formations in San Fernando area show that orogenic movements took place locally at various times, but the mid-Pleistocene orogenic epoch overshadowed all the others in intensity. During the faulting and accompanying folding, the massif of pre-Tertiary crystalline rocks behaved essentially as a competent block undergoing intermittent elevation, with adjustments within that block accomplished by faulting, shearing, and fracturing.

THE SIERRA MADRE FAULT ZONE

The Sierra Madre fault zone is a series of arcuate convex-southward reverse faults which generally separate the pre-Tertiary crystalline rocks on the north from Cenozoic sedimentary formations on the south. The faults are discontinuous and of variable dip from 15° to near-vertical; all dip northward, with the crystalline rocks thrust upward toward the south over Quaternary sediments and the mid-Pleistocene Pacoima Formation; some, of course, are post-alluvium. Displacements have been essentially of the dip-slip type and are as great as 600 m on any one fault. The fault zone (figure 3) is comprised of the following discontinuous faults, from west to east: the Grapevine, Sombrero, Hospital, Buck Canyon-Watt, an unnamed fault in upper Kagel Canyon, Lopez, Sunland, and Rowley faults, and probably continues eastward along the entire front of the San Gabriel Mountains. "Sierra Madre" came from an old name for the San Gabriel Mountains, not from the town of Sierra Madre. Eastward, the Sierra Madre fault zone appears to cut across the right-lateral southeast-trending San Gabriel fault and continue as the frontal fault of the San Gabriel Mountains north of the town of Sierra Madre. The San Fernando fault of February 9, 1971, must cut the San Gabriel fault at depth, as seen in geologic section (figure 4).

The Grapevine and Sombrero faults, and subsidiary lesser faults, represent continuing faults in the northeast end of the Santa Susana thrust-fault zone. The Grapevine fault is exposed on a very steep, high, topographic slope where the Placerita Formation-diorite-gneiss complex has been thrust, at angles of 40° to 50°, or steeper, over folded and disturbed beds of the early Pliocene Elsmere Member of the Repetto Formation. The north-trending Sombrero fault shows the same relationships but has a near-vertical dip in Sombrero Canyon. Hill 1876 is an interesting klippe of the crystalline-rock complex lying on the lower Pliocene Elsmere Member. Careful inspection leaves this feature open to various interpretations, but it seems most likely that the klippe represents a mid-Pleistocene subsidiary gravity fault along the front of an active Grapevine fault.

The Hospital fault strikes due east for 2 miles along the steep mountain front from Olive View Sana-

Photo 8. Hill 1876, a klippe of Late Paleozoic (?) crystalline rocks lying in fault contact on lower Pliocene Elsmere sandstone. The hill in left background consists of the crystalline rocks thrust over Elsmere along the Grapevine fault. The lower right white roadcut is in Saugus gravel, separated from the Klippe by the Sombrero fault.

torium to the Veterans Administration Hospital. The fault dips from 45° to 60° N and has thrust crystalline rocks over the strongly folded fanglomerate of the mid-Pleistocene Pacoima Formation; the fault does not appear to have displaced Late Quaternary terrace gravels, but this remains uncertain. It can be approximately traced throughout most of its course, but the precise contact is usually obscure. Apparent dip of this fault, as well as that of the east-west portion of the Grapevine fault, may have been lowered by slumping on the steep slope; dip at depth is probably steeper. Barrows (this Bulletin) does not consider the Hospital fault to be important and does not consider that it extends west of Loop Canyon; however, it appears to cut out the north limb of the Little Tujunga syncline (Oakeshott, 1958); and immediately south of the fault, in the axis of the western prolongation of the Little Tujunga syncline, crystalline basement lies at a depth of more than 12,000 feet in Sunray Oil Company Stetson-Sombrero 1 (Oakeshott, 1958). Thus, the total of downfolding and throw on the Hospital fault must be on the order of 4 km (2½ miles). This *could* be attributed predominantly to folding, rather than faulting; Barrows certainly mapped on a much larger scale and spent much more time on the area than I did.

The Buck Canyon-Watt fault marks the northwest and northern limit of the Saugus Formation in the Little Tujunga area. The Buck Canyon fault strikes generally N 75° to 85° E and continues toward the east as the Watt fault. The plane of the Buck Canyon-Watt fault dips generally northward; but the dip is variable, usually between 45° and 75°. Cretaceous granodiorite has been thrust over the Saugus Formation along the Buck Canyon section of the fault; along most of the length of the Watt fault, the upthrown side consists of the Paleocene "Martinez" Formation caught between that fault and the DeMille branch of the San Gabriel fault. At the head of Lopez Canyon, the loop and anomalous reversed dip in the Buck Canyon fault are probably Late Quaternary landslide effects. Saugus strata steepen rapidly from south to north, approaching the Watt fault, until at the contact attitudes of bedding equal those of the fault plane. Martinez beds on the upthrown side are contorted and fractured. Throw is at least 600 m as inferred from the fact that the base of the Saugus Formation along Gold Creek if projected northward, downdip, would intersect the fault plane at least 600 m below the surface; Saugus beds do not appear north of the fault. Displacement on the fault lessens toward the west; in upper Buck Canyon an estimate of 300 m of vertical displacement can be made. The fault steepens and dies out in granitic rocks in Limekiln Canyon. At the eastern end of the Buck Canyon-Watt fault its several elements strike into the San Gabriel fault zone.

From upper Kagel Canyon to Buck Canyon a northeast-trending reverse fault dipping 25° NW has thrust the crystalline rocks over Saugus strata. The fault has a throw of 60 to 200 m. At its southwest end, trend of this fault swings about to parallel the Lopez fault, and may merge with it.

The Lopez fault strikes generally N 70° W as it crosses Kagel and Lopez Canyons. It continues eastward to within 500 m of Little Tujunga Canyon where its strike changes abruptly to N 35° E. Where the strike is westerly, dip of the fault is from 50° to 75° N; at the type locality in Lopez Canyon it is 50° N. An overturned anticline with due east strike at Lopez Canyon strikes acutely into the fault and plunges 25° W. This minor fold on the south side of the fault and the swing in strike of the fault in Kagel Canyon in the north block suggest a possible small right-lateral component of displacement in this part of the Lopez fault. Just east of upper Kagel Canyon is the small De Oro branch fault (Hill, 1930) with a well-exposed plane dipping 5° N which is cut off by another dipping 60° N. The block of granitic rock here lying on a 5° slope, like the Sombrero klippe, probably represents post-Saugus gravity slumping along the steep scarp of a reverse fault. Displacement along the Lopez fault dies out to the north in Little Tujunga Canyon and at the west end in Pacoima Canyon. Maximum vertical displacement may be estimated near the major bend of the fault, using the base of the Saugus Formation as the reference plane; this gives a figure of about 250 m.

The Sunland fault is another element of the Sierra Madre fault zone which is complicated by several subsidiary faults, although it is essentially a reverse fault with granodiorite thrust over sedimentary rocks as young as the Saugus Formation. Slivers of middle(?) Miocene Topanga volcanic rocks and the upper Miocene Modelo Formation lie between branches of this fault. Strike of the Sunland fault varies from N 65° W in its western part to N 25° E near its eastern end where the fault dies out in granitic rocks in Tujunga Canyon. Exposures of the north plane show near-vertical dips but mapping of the Sunland fault proper shows north dips of about 50° at the type locality just west of Ebey Canyon. Saugus and Modelo strata steepen and are overturned at the fault. Perfectly exposed Saugus beds lying unconformably on gneiss in Little Tujunga Road and similar contacts 600 m farther southeast preclude the extension of the fault northwestward beyond Herreres Ranch. An exploratory well, Intex Cleeves 2 (Oakeshott, 1958), in Cottonwood Glen passed through the Saugus Formation at a depth of 1,505 feet, indicating the absence of any significant fault. Thus the Sunland fault dies out under a rock slide near Herreres Ranch. Maximum vertical displacement on this fault must be quite large, possibly 600 to 1,200 m.

The Rowley fault is the most easterly group of faults in the Sierra Madre fault zone discussed here. In the town of Tujunga, the most easterly of three fault planes is a 15 m-wide zone of brecciated granodiorite with a N 25° W strike and a vertical dip. The main Rowley fault plane, next west, is not perfectly exposed; its dip is obviously east and granodiorite is thrust over very coarse east-dipping conglomerate of the lower Pliocene Repetto Formation. The latter is faulted against west-dipping basalt flows of the middle (?) Miocene Topanga Formation.

Mission Hills Faults

A fault zone, comprising three faults, is perfectly exposed in Sepulveda Boulevard road cuts at the southeastern margin of Van Norman Reservoir in the Mission Hills. Most southerly of these fault planes is a reverse fault that dips 60° S and thrusts rocks of the Modelo Formation on the north limb of the Mission Hills anticline over the lower Pliocene Repeto Formation. The next fault north dips 55° S and has thrust Repetto sandstone over fossiliferous sandstone of the middle Pliocene Lower Pico Member of the Pico Formation. The most northerly of the group is a normal fault dipping 75° N, which has dropped upper Pliocene Sunshine Ranch beds against Lower Pico.

A north-dipping Mission Hills thrust was postulated, supported by the anomalous geologic section reported in Universal Consolidated well Panorama 1 (Oakeshott, 1958). It was argued that, if such a fault exists, it might be expected, by analogy, to have features similar to faults of the Santa Susana-Sierra Madre zone. That is, its trace should be convex southward, its trend should turn to northerly around the eastern end of Mission Hills, it should dip about 40° to 50° N, and it should die out within a mile or two, both east and west. The southwestern end of the 1971 San Fernando fault may well be part of the Mission Hills thrust.

Pacoima Hills Fault

A well-exposed east-trending normal(?) fault, dipping 50° N, in the Pacoima Hills has brought granodiorite up on the south side against sedimentary and volcanic rocks of the Topanga Formation. Four miles east, in the Verdugo Hills, these formations are in unconformable contact. Viewing the Pacoima Hills as a westward outlier of the Verdugo Hills structural high, this fault may be of small displacement. Bailey and Jahns (1954) projected it 5 miles east as a buried fault along the south side of Tujunga Valley. However, the most reasonable structural section appears to show no necessity for a Tujunga Valley fault with large throw.

The San Fernando Fault, 1971

The fault which caused the earthquake of February 9, 1971, is thoroughly discussed in this Bulletin by many authors. Allen and Bolt, for example, each discuss its characteristics from the seismic records; Kahle, Barrows *et al.* have mapped it and recorded its geological characteristics in great detail (plate 2). I wish only to call attention here to a few of the pertinent features of this active fault in the context of its place in the Sierra Madre fault zone.

1) Hypocenter of the earthquake was north of the San Gabriel fault at a depth of about 8 km in brittle, crystalline gabbroic rocks and/or gneisses of relatively high density and high seismic-wave velocities;

2) The initial rupture, on a fault surface dipping about 50° N, progressed upward and southward through perhaps five formations of decreasing density (Precambrian gabbro or gneiss, Cretaceous granodiorite, Tertiary volcanics, Tertiary marine sediments, and Quaternary sediments. Near-surface Quaternary gravels (including Saugus, the oldest) extend to depths of as much as 4 km in the area. The fault must have cut and displaced the San Gabriel and Hospital fault surfaces (See Geologic Structure Section, figure 3). Near-surface dip of the San Fernando fault surface was 20° or less; average dip was about 35°.

3) Detailed, large-scale mapping and measurement of any attitudes of the fault surface in outcrop have demonstrated highly irregular and variable attitudes but predominantly low dips;

4) The Lakeview-Tujunga segment of the fault strikes N 70° W; the Sylmar segment strikes due W; and the Santa Susana segment strikes SW—thus, the fault surface is a complex, warped surface. The discontinuity in the trace at its right-angle turn in lower Pacoima Canyon suggests a tear or break in the fault surface there (Sharp, this Bulletin).

5) The surface of crystalline bedrock below the Tertiary-Quaternary sediments of the San Fernando basin is extremely steep and has high relief (Oakeshott, 1958); for example, the crystalline rock surface exposed in the Verdugo Mountains-Pacoima Hills plunges westward over 400 m per km.

Even the short review of structural history in this paper shows that, geologically, February 9, 1971, was merely the latest repetition of a pattern which was established in mid-Pleistocene time at least a million years ago.

Relationship of Damage to Geology

Steinbrugge and others, writing in this Bulletin, have noted the concentration of building damage a) along the fault trace, and b) in a second belt closer and parallel to the mountain front in the Sylmar segment of the fault. Of course, reasons for damage to buildings in the fault trace are obvious. Furthermore, the width of ground rupture and zone of fault-trace damage are relatively great because of the low dip of the fault. Damage tends to be concentrated in the upper plate, partly because it is thin and vulnerable to failure and partly—in this case—because the upper plate did the active moving.

Reasons for concentrated damage in the belt along the mountain front are less obvious, but this damage zone coincides with the axis of the Little Tujunga syncline where the loosely consolidated Quaternary sediments reach extraordinarily great depths.

The "topographic" effect of the high-relief surface of crystalline bedrock which underlies the Quaternary and Tertiary sediments of the basin gives opportunity for complexities of near-surface earthquake waves and ground response. Here is a fertile model for study.

CHAPTER 4

Ground Water Geology of the San Fernando Valley[1]

by Glenn A. Brown [2]

The author of this paper intends to set forth the hydrogeologic framework of the San Fernando Valley as it was developed prior to the February 9, 1971, earthquake and to appraise the effect of that earthquake on ground water conditions in the vicinity of the city of San Fernando.

Most of the hydrogeologic information in this paper was prepared by the author for the State Water Rights Board, which was appointed Referee in 1958 in the case *City of Los Angeles vs. City of San Fernando et al.* The history of litigation over water in the Upper Los Angeles River Drainage Basin assists greatly in the understanding of the recharge, occurrence, and movement of ground water in San Fernando Valley. A brief history of litigation is included in this paper.

The total ground water storage capacity of the San Fernando Valley has been estimated to be in excess of 3,500,000 acre-feet. A more precise estimate is not obtainable due to the unknown depth of the water-bearing deposits in the east-central parts of the valley. Studies of the change in storage utilizing the specific yield method indicated that about 600,000 acre-feet had been removed from storage from the historic high-water levels in 1944 to the lowered water levels in 1957.

Several hydrologic "subareas" were established for use in the Report of Referee. These were the San Fernando hydrologic subarea, the Sylmar hydrologic subarea, the Verdugo hydrologic subarea, and the Eagle Rock hydrologic subarea. The subareas were established for purposes of description and data tabulation. The subareas are separated from each other by faults, folds, alluvial constrictions, or man-made works. The San Fernando subarea is subjacent to each of the other subareas and receives surface drainage from all of them. The Sylmar, Verdugo, and Eagle Rock subareas are not directly interrelated or interdependent upon one another.

Brief History of Litigation

Litigation over water has been one of the primary motivations to seek a better understanding of the origin, occurrence, and movement of ground water within the San Fernando Valley (Upper Los Angeles River Drainage Basin). The history of water rights in California is one of numerous judicial decisions as a result of litigation between water users in the watershed of the upper Los Angeles River. This brief history is included to provide an understanding of the legal problem and how geologic studies have been used.

The Pueblo of Los Angeles was founded by land-grant proclamation in 1781. The proclamation gave title to an area of approximately 28 square miles and the rights to take the waters of the Los Angeles River for municipal use.

The first known test of the grant was in 1810, when certain citizens of Los Angeles reported to the Spanish Military Commander at Santa Barbara that the Fathers of Mission San Fernando had built a dam diverting water that supplied the Pueblo. The committee appointed to investigate reported that the dam was causing suffering and damage. The Mission Fathers finally acknowledged the superior rights of the Pueblo. They did ask, however, for permission to use sufficient water for irrigating land necessary to the Mission. This was granted with the definite understanding that they would cease to use the water whenever the Pueblo decided that such use was causing a diminution of the needed municipal supply.

The Act of 1850, which incorporated the City of Los Angeles under American rule, provided that the City should succeed to the property rights and powers of the Pueblo.

In the case *Feliz vs. Los Angeles* in 1881, it was clearly stated that the City of Los Angeles had a right to all of the waters of the Los Angeles River if required for municipal purposes or for use of its inhabitants. This action was brought by Anastacio Feliz against the City for cutting water off from his irrigation ditch. The lower court decided against the city, but the upper court reversed the decision.

In 1903, the case of the *City of Los Angeles vs. Los Angeles Farming and Milling Company* was heard, and the decree stated that the Company had no right to take or use the waters of the Los Angeles River except in subordination to the paramount right of the City of Los Angeles.

The case of *City of Los Angeles vs. Laguna Irrigation Company* in 1904 had a similar outcome with the exception that all diversion works were to be removed.

The geographic setting of the case of *Burr vs. Maclay Rancho Water Co.*, 1908, was in the vicinity of the City of San Fernando and removed from the main tributaries of the Los Angeles River. The case is of interest because it was held that the trial court had the power to make reasonable regulations for the

---

[1] Submitted for publication June 12, 1972.
[2] Glenn A. Brown & Associates, Consulting Geologists.

use of the common supply of ground water by the respective parties. The decision fixed times during which each party might withdraw water, as well as the quantities that might be withdrawn.

The decision in *Los Angeles vs. Buffington et al.*, 1909, was one of the more important ones in field of water rights in that surface water and ground water were for the first time interrelated. The State Supreme Court made the following classic analogy: "Unquestionably the San Fernando Valley is a great natural reservoir and supply of the Los Angeles River. Unquestionably the cutting off of this supply would as completely destroy the Los Angeles River as would cutting off the Great Lakes destroy the St. Lawrence." With legal cornerstone firmly in place, the City of Los Angeles filed the next noteworthy action in 1938: *Los Angeles vs. Glendale and Burbank.* This case was decided in favor of the City of Los Angeles, upholding the Pueblo Right; however, the defendants were allowed to continue the use of the water as long as there was a surplus, in other words, as long as the basin was not being overdrafted.

Due to the decline in ground water levels, the City of Los Angeles filed a new action in 1955, *City of Los Angeles vs. City of San Fernando et al.* This case had over 200 defendants, each of whom used more than 1 acre-foot of ground water per year.

In June of 1958, the State Water Rights Board was appointed Referee by the court under Section 2001 of the California Water Code. The Referee was ordered to prepare a factual report that would serve as "prima facie" evidence within the framework of the Order of Reference. Certain items of the Order of Reference contain the subject material for this paper.

"I.1 The geographic and hydrologic boundaries of the watershed of the Los Angeles River and its tributories above the junction of the surface channels of the Los Angeles River and the Arroyo Seco at a point designated as Los Angeles County Flood Control District Gaging Station F-57."

The watershed above Gage F-57 contains 329,000 acres, of which 206,000 acres are classed as hill-and-mountain areas and 123,000 acres are valley floor. The Los Angeles River is the principal stream draining the watershed. The Verdugo, Big Tujunga, Little Tujunga, Pacoima, Bull Canyon, Aliso, Browns Canyon, Dayton, and Bell Creeks and Arroyo Calabasas constitute the major secondary streams which are tributary to the Los Angeles River.

"I.2 The complete geology insofar as it affects the occurrence and movement of ground water and the surface and ground water hydrology of said area".

The Report of Referee was completed in July 1962. The author of this paper was responsible for the preparation of the geologic and water-quality sections of that report while in the employ of the California Department of Water Resources.

The trial court in the case *City of Los Angeles vs. City of San Fernando et al.* found in favor of the defendants by ruling that prescriptive rights prevailed over the City of Los Angeles Pueblo Rights. This case is currently under appeal.

A prescriptive right to the use of water is based on continuous use adverse to prior rights for five years and failure of the owners of the prior rights to file legal action to protect themselves during that time. Action by the owner of prior rights then becomes barred by the statute of limitation and the right of the subsequent appropriator is called a prescriptive right to use of water.

Previous Investigation

Previous bulletins and papers that dealt primarily with the geology near the area of investigation pertain mainly to the sedimentary and crystalline rocks in the hills and mountains around the edges of the valley fill.

Several authors have divided the area under investigation into numerous basins and subbasins. For the most part, these divisions were made at or near locations where there is a change in ground water storage capacity, a drainage (topographic) divide, structures that retard the flow of underground water toward the Los Angeles Narrows or a combination of these physical features.

California State Department of Public Works, Division of Water Resources, "South Coastal Basin Investigation, Geology and Ground Water Storage Capacity of Valley Fill", Bulletin No. 45, 1934, contains detailed and broad coverage of the geology of the area and the interrelationship of the geology and the ground water. Particular reference is made to the geologic features of the valley fill and to the water-bearing rocks. This work has been studied in detail, and data pertaining to specific yield and storage capacity have been slightly modified and utilized in the present report. The modifications were based on an additional 25 years of records and data.

The earlier publications, mainly geologic in nature, that were utilized in the study are (see Consolidated References, this Bulletin):

Bailey, T., and Johns, R., 1954; Buwalda, J. P., 1940; Corbato, E. E., 1960; Dudley, Paul, Jr., 1954; Hill, M. L., 1931; Hoots, H. W., 1931; Jennings, C. W., and Hart, E. W., 1956; Kew, W. S. W., 1924; La Rue, E. C., 1943; Miller, W. J., 1934; Neuerburg, G. J., 1953; Oakeshott, G. B., 1937; Oakeshott, G. B., 1958; Schaellhamer, J. E., Vedder, J. G., and Yerkes, R. F., 1954; Thayer, W. N., 1945; Weldon, John, Jr., 1955; Winterer, E. L., and Durham, D. L., 1958.

Well-Numbering System

The well-numbering system used here is that used by the Los Angeles County Flood Control District. The first two numbers represent the officially assigned number of the old 6-minute quadrangle series that covered Los Angeles County. Each quadrangle was divided into a grid system with the number 1 through 9 plus 0 being assigned to both the abscissa and the ordinate. A letter designation after the numbers indicates that there is more than one well within a given grid location. A well number 4850-B would therefore be located on quadrangle number 48; 5 represents the abscissa and 0 the ordinate location; and B indicates that this is the third well to be constructed in that grid section.

Hydrologic Subareas

The valley floor is in general an alluvium-filled basin approximately 23 miles long and 12 miles wide.

Based on physiography and geologic features, the valley has been divided into the four hydrologic subareas already discussed: the San Fernando subarea, the Sylmar subarea, the Verdugo subarea and the Eagle Rock subarea. Little is known of the depth of alluvium in the central and eastern part of the San Fernando subarea, but it may exceed 1,000 feet west of Burbank.

The geologic events which affected the valley floor and the bordering hills and mountains as a whole during formation of the structural features must be considered, as well as features now expressed by topography, in order to depict their effect on the occurrence and movement of ground water.

GEOLOGIC FORMATIONS

The geologic formations may be divided into two general groups: the nonwater-bearing rocks and the water-bearing rocks.

The nonwater-bearing rocks do not absorb, transmit, or yield water readily. They are the "Basement Complex" rocks and the Cretaceous and Tertiary sediments of the "Chico" formation and the Martinez, Domengine, Topanga, Modelo (Puente), Repetto, and Pico Formations. Water wells pumping from these rock units generally yield less than 100 gallons per minute.

The water-bearing rocks—all of which absorb, transmit, and yield water readily—consist of alluvial deposits of Quaternary age and include the Saugus Formation, older alluvium (including "terrace" deposits), and Holocene alluvium. This study deals mainly with the character and extent of the water-bearing rocks. Properly designed and constructed water wells may yield more than 2000 gallons per minute from these rock units.

The stratigraphy of the area of investigation is shown in table 1.

The geological mapping performed by many previous workers has been compiled and supplemented where necessary by work of the staff of the Water Rights Board and is presented as figure 1, "Areal Geology".

Nonwater-Bearing Rocks

The nonwater-bearing rocks, which are made up of relatively impervious formations that underlie and surround the more pervious formations, differ from the water-bearing rocks in three respects: (1) the nonwater-bearing rocks are for the most part relatively impervious and therefore store comparatively little water which they yield to wells very slowly; (2) where pervious beds or zones occur within the nonwater-bearing rocks, the movement of ground water and recharge from outcrops is generally so restricted by faults, structural position, or physical character of the materials that supplies of water obtained from such beds or zones are too limited to be comparable to ground water supplies obtainable from the water-bearing rocks; and (3) the quality of the water found in some of these rock units is generally unsuitable for most beneficial uses.

There are several types of openings in the nonwater-bearing rocks, including: original interstices in porous beds of the sedimentary rocks; interstices in the weathered zone; fractures and joint openings below the surface (including openings along bedding planes and planes of schistosity); and openings caused or enlarged by solution of the country rock.

In most places, both the sedimentary and crystalline nonwater-bearing rocks are so impervious that they yield very little water to wells and consequently are of no value except for domestic or stock-watering purposes. The limited amount of water contained in the nonwater-bearing series in the hill and mountain areas is available for transpiration and evaporation, and for effluent stream flow. Since the rate of movement of water through the nonwater-bearing rocks is generally slow, water derived from one season's precipitation may be held over for ensuing years. In a few places, pervious strata or fracture zones in the nonwater-bearing rocks may yield water freely to wells. However, in most cases such production is short lived because of the relatively small storage capacity and inadequate recharge areas.

Water-Bearing Rocks

Ground water occurs in three principal water-bearing formations: the Pleistocene Saugus Formation (including upper Pliocene Sunshine Ranch beds), Late Quaternary older alluvium (including Pacoima Formation and terrace deposits), and Holocene alluvium.

Lower Pleistocene Saugus Formation. The Saugus Formation in the San Fernando Valley is generally restricted to marine and terrestrial deposits of probable lower Pleistocene age (Oakeshott, 1958) usually lying with angular unconformity on formations of all ages from the Basement Complex to the Pico Formation.

The Saugus Formation crops out in the hills and southern flanks of the mountains along the northern portion of the valley floor and underlies the other water-bearing sediments. The maximum thickness is 6400 feet as measured on the east side of Lopez Canyon. Two miles east of Little Tujunga Canyon, the formation thins rapidly to 2000 feet. The formation also thins in a southwesterly direction to about 3000 feet at the Van Norman Reservoirs. There are no outcrops of the Saugus Formation in the Santa Monica Mountains, Simi Hills, or Verdugo Mountains, indicating that the formation is restricted to the northern portion of the valley.

The water-bearing portion of the Saugus Formation consists of light-colored, poorly sorted, loosely consolidated conglomerate and coarse sandstone, commonly cross-bedded, which were deposited as fluviatile and alluvial fan sediments. Throughout the Saugus Formation, layers and lenses of clayey gravel have been formed by weathering of the original materials in place.

In general, the water-bearing capacity of the Saugus Formation is somewhat lower than the older alluvium (terrace deposits).

Upper Pleistocene older alluvium (terrace deposits). The lower, more folded portions of the older alluvium have been differentiated by some investigators from the less folded deposits and the name Pacoima Formation (Oakeshott, 1958) has been proposed for

Table 1. Stratigraphy in Los Angeles River watershed.

	Age	*Geologic unit*	*Description*	*Remarks*	*Thickness in feet*
Quaternary (water-bearing)	Holocene	Alluvium	Poorly sorted, unconsolidated, coalescing alluvial fan deposits of sand, gravel, and clay. Generally undissected and undeformed.	More gravel in eastern part of valley; finer grained in western portion of valley with high clay content.	0–100±
			—Local unconformity—		
	Late Pleistocene	Older alluvium, terrace deposits, and slightly folded Pacoima Formation.	Alluvial terrace deposits around basin-margin and thick series of poorly consolidated continental gravel, sand, and clay. Characteristic red or brown weathered surface. Deformation generally slight at surface but increases with depth. Some layers of fossil soils.	Generally more clayey and compacted than Holocene alluvium. More gravelly in east and more clayey in west.	0–2000±
			—Local unconformity—		
	Early Pleistocene	Saugus Formation (Sunshine Ranch beds included).	Folded continental and marine, poorly consolidated conglomerate, sand, silt, and clay.	Continental alluvial fan deposits along north central portion of valley; finer marine sediments to west. Not found along southern or eastern portion of valley.	0–6000±
			—Local unconformity—		
Tertiary (nonwater-bearing)	Late Pliocene	Pico Formation	Blue sandy shale and siltstone with sandstone and conglomerate lenses. Principally marine. Consolidated and cemented.	Found only along northern portion of valley.	1500–3000±
	Early Pliocene	Repetto Formation	Marine blue and brown siltstone and mudstone, arkose, sandstone, and conglomerate. Some fossiliferous and petroliferous beds.	Found only along northern portion of valley.	400–3000±
			—Local unconformity—		
	Late Miocene	Modelo Formation (called Puente Formation at Los Angeles River Narrows)	Alternating marine shale and sandstone members. Thin-bedded cherty shale, diatomaceous shale, and diatomite varying to clayey and sandy facies. Thick coarse massive arkosic sandstone and conglomerate with interbedded fine sandstone and shale. Sharp local variations. Associated with intrusive and extrusive basalt and other igneous rocks.	Found around the perimeter of the valley but probably underlies whole valley.	4000–7000±
			—Local unconformity—		
	Middle and/or early Miocene	Topanga Formation	Northern portion of valley continental arkose, conglomerate, red and yellow beds. Interbedded andesite and basalt flows. Southern and western portion of valley principally marine with some continental beds in lower part.		700–7500±
			—Unconformity—		
	Middle Eocene	Domengine Formation (Meganos Formation)	Marine gray to greenish, hard calcareous sandstone and conglomerate.	Small outcrops in hills and mountains in northwestern portion of valley.	650±
			—Local unconformity—		
	Paleocene	"Martinez" Formation	Marine greenish-black sandstone, dark shale, coarse conglomerate.	Found along DeMille fault in San Gabriel Mountains and in Simi Hills at western tip of valley.	250–900±
			—Unconformity—		
Cretaceous (nonwater-bearing)	Late Cretaceous	"Chico" Formation	Upper portion marine massive hard coarse conglomerate with some sandstone and shale; lower portion soft red conglomerate and sandstone. Probably continental deposit.	Found in hills and mountains around western portion of valley.	250–900±
			—Unconformity—		
Pre-Tertiary Basement Complex (nonwater-bearing)	Cretaceous or Jurassic	Granodiorite, granite, quartz diorite, etc.	Granitic intrusion.		
	Jurassic (?)	Santa Monica Slate	Black slate with schist facies.	Santa Monica Mountains south of Encino Reservoir.	5000–7000±
	Pre-Cretaceous	Pelona Schist, Placerita Formation, and others	Undifferentiated metamorphic and granitic rocks, schist, gneiss, and a variety of crystalline rocks.	Found in San Gabriel Mountains, Santa Monica Mountains, Verdugo Hills, and San Rafael Hills.	

this middle Pleistocene deposit. Except for the more pronounced folding and overthrusting of Basement Complex, there is little difference between this unit and the remainder of the older alluvium.

The older alluvium was derived from deposits left by modern streams in earlier cycles of erosion with the source areas little different from those of the present streams.

Lithologically, the materials in all the older alluvium and terraces are broadly similar, consisting of brown to grayish, dirty, unsorted, angular to subangular detritus, entirely of local origin. There are numerous breaks in the deposition of the material during which extensive weathering took place, forming horizons of ancient soils. Consolidation is poor, and the deposits are only locally cemented. Deposition of alluvial materials now taking place indicates that topography and drainage were nearly similar when the older alluvial deposits were being laid down. The belts of terrace deposits are broader than present stream deposits in some places and were probably formed by streams flowing at slightly lower gradients and in broader valleys. This would be a logical explanation, in part, because of the finer grained nature of some of the older alluvium as compared to the Holocene deposits. The main explanation for the higher clay content is the formaion of residual clays by weathering.

The water-bearing character of these deposits is variable, depending upon the source area. West of the vicinity of Van Norman Reservoir and along the southern boundary of the valley, local streams from the hills have deposited fine debris derived from the predominantly sedimentary rocks of that region. East of Van Norman Reservoir, Pacoima Creek, Big Tujunga Creek, Little Tujunga Creek, Verdugo Creek, and other streams have deposited alluvial cones which consist almost entirely of coarse crystalline debris from the mountains to the north and east.

Holocene alluvium. Rejuvenation caused increased gradients of the streams tributary to the Los Angeles River at the close of Pleistocene time and accelerated erosion from the mountains and deposition in the valley. Holocene deposits east of Pacoima Wash and north of the Los Angeles River consist of predominantly coarse, thick accumulations of boulder, gravel, and sand in coalescing alluvial fans, becoming finer grained farther from the canyon mouths. West of Pacoima Wash and south of the Los Angeles River, the sediments were derived from predominantly sedimentary rocks, are finer grained, and were deposited in much the same manner as the underlying older alluvium.

Character of Quaternary water-bearing alluvium. As previously stated, the sediments in the western portion of the valley floor are of a different nature than those found in the eastern portion and, therefor, have different water-bearing characteristics.

It was not possible to distinguish the Saugus Formation from the older alluvium by using the available well logs, with the exception of the Sylmar hydrologic subarea, so it was assumed that in all other areas the two formations had similar water-bearing characteristics.

Well logs show the western part of the valley floor to have an average of about 75 percent clay, 5 percent sand, and 20 percent gravel. Although the smaller streams of this area probably bring down considerable amounts of fine material, the low percentage of sand compared to gravel suggests that the finer grained components have been decomposed to clay. These sedimentary materials probably break down more readily under the influence of weathering than do the crystalline rocks in the eastern portion of the valley. An average analysis of material from wells of the coarser crystalline material in the eastern portion of the valley floor shows 20 percent clay, 35 percent sand, and 45 percent gravel. These deposits were originally coarser than those farther west and apparently do not break down as quickly through weathering. The coarser grained materials exhibit noticeable difference in directional permeability.

STRUCTURAL FEATURES

The structure of the Upper Los Angeles River Area is rather complicated. The rough topography of the Basement Complex and extensive folding and faulting of the rocks in the hills and mountains indicate that the older rocks beneath the alluvium of the valley are folded and possibly faulted; therefore, the overlying alluvium probably varies in thickness. With the exception of the faulting and folding along the northern half of the valley, there is no definite evidence that any of the other faults or folds have influenced the Holocene alluvium.

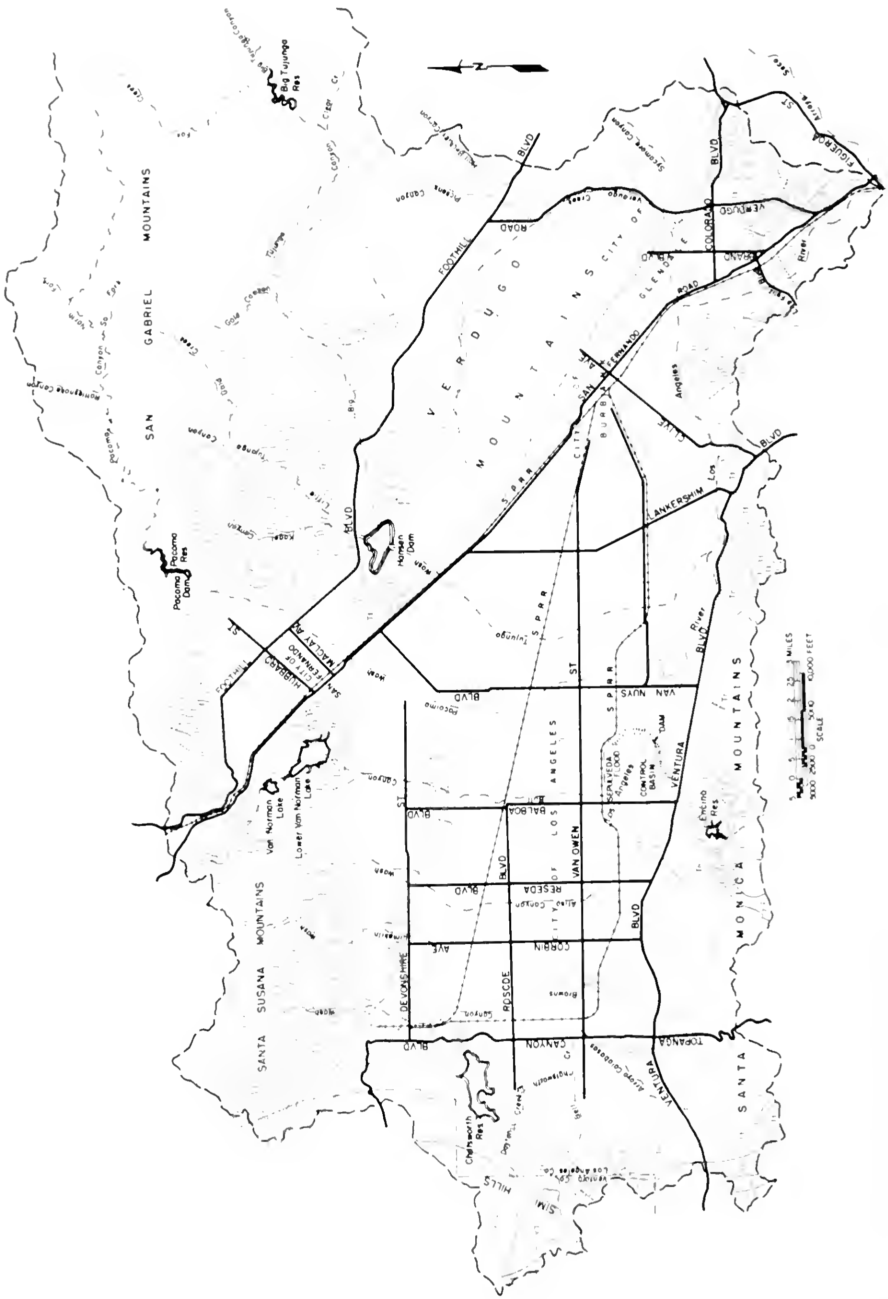
Faulting

Structure of the area is dominated by the San Gabriel fault system. The north dipping thrust faults of the Sierra Madre fault zone of the San Gabriel Mountains, the Santa Susana thrust fault in the Santa Susana Mountains on the north, and the faulted anticlinal structure of the Santa Monica Mountains on the south are also important fault features.

San Gabriel fault zone. The San Gabriel fault zone has strong topographic expression—the faults appearing prominently on aerial photographs because of displaced geologic units, offset drainage, strike valleys, notched ridges, subparallel faulting, fracturing, and folding.

Verdugo fault zone. The Verdugo fault zone along the south edge of the Verdugo Mountains, approximately parallel to San Fernando Road, and the Eagle Rock fault to the east appear to be a part of, or are related to, the San Gabriel fault system.

Sierra Madre fault zone. The Sierra Madre fault zone is a series of curved, convex-southward, reverse faults, which separates nonwater-bearing sedimentary and pre-Tertiary crystalline rocks on the north from the Cenozoic sedimentary formations on the south. The faults are discontinuous and dip from 15 degrees to vertical; all dip northward with the older sedimentary and crystalline rocks thrust upward toward the south over sediments as late as the mid-Pleistocene Pacoima Formation of the water-bearing series. Displacements have been essentially of the dip-slip type and are as great as 2,000 feet on any one fault. Dis-


SAN GABRIEL MOUNTAINS
VERDUGO MOUNTAINS
SANTA SUSANA MOUNTAINS
SANTA MONICA MOUNTAINS
SIMI HILLS
Big Tujunga Res
Pacoima Res
Pacoima Dam
Hansen Dam
Van Norman Lake
Lower Van Norman Lake
Chatsworth Res
Encino Res
SEPULVEDA FLOOD CONTROL BASIN DAM
CITY OF SAN FERNANDO
CITY OF GLENDALE
CITY OF BURBANK
CITY OF LOS ANGELES
FOOTHILL BLVD
SAN FERNANDO ROAD
LANKERSHIM BLVD
VAN NUYS BLVD
BALBOA BLVD
RESEDA BLVD
CORBIN AVE
DEVONSHIRE
ROSCOE BLVD
VAN OWEN ST
VENTURA BLVD
TOPANGA CANYON BLVD
COLORADO BLVD
VERDUGO ROAD
FIGUEROA ST
HUBBARD ST
MACLAY AVE
S P R R
SCALE
MILES
FEET

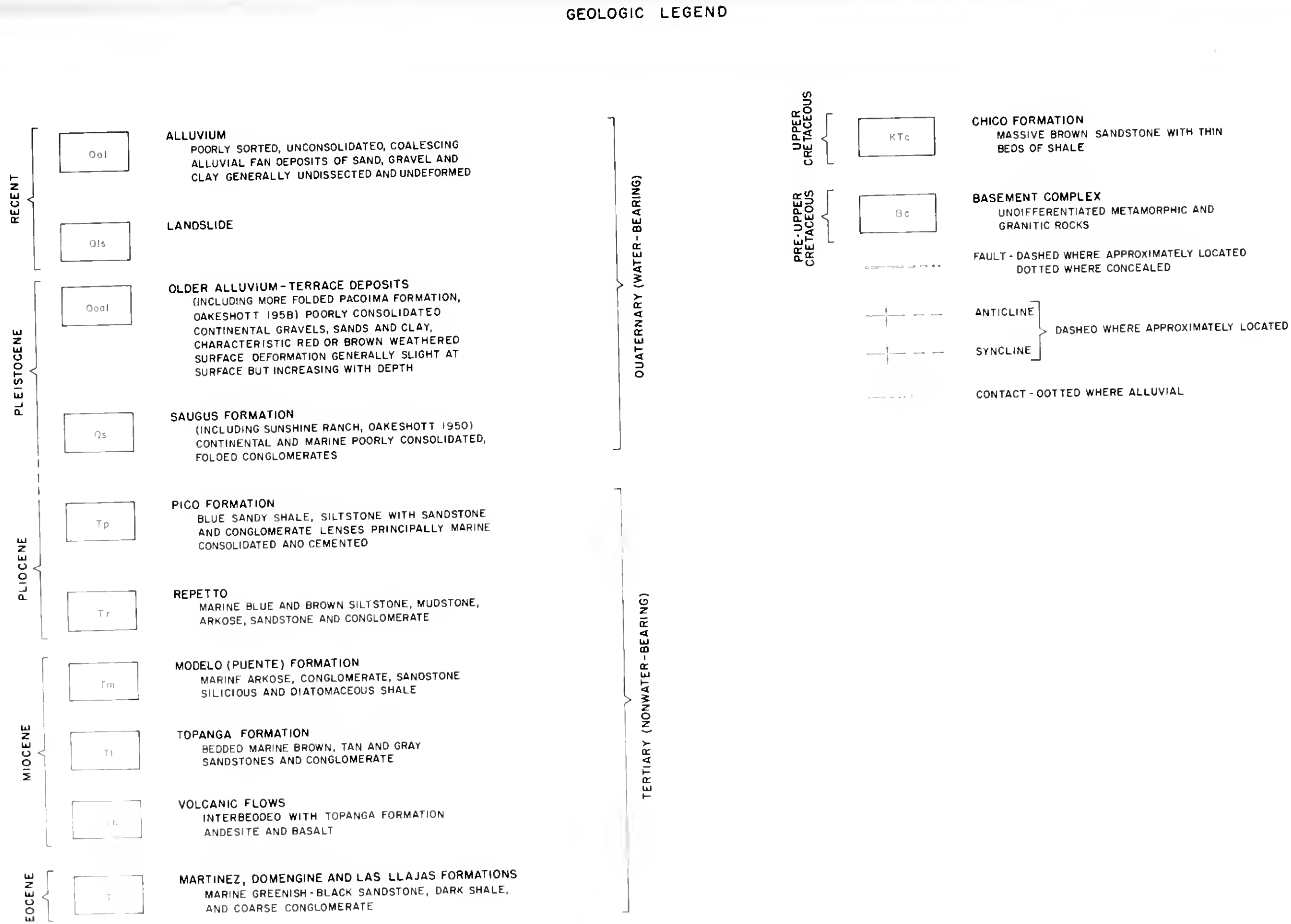


Figure 1. Areal geology, San Fernando Valley.

placement rapidly dies out as the strike of each of these reverse faults changes from the general east-west trend to a more northerly trend.

Northridge Hills fault. The Northridge Hills fault is a high-angle fault. Knowledge of its existence is based primarily on the numerous oil test holes which have been drilled in the Northridge Hills. Logs of these wells indicate that the Modelo Formation has been displaced between 500 and 1,000 feet along the dip of the fault. The apparent movement along the fault has been dip-slip with the north block up.

Mission Hills fault. A minor fault zone comprising three faults is perfectly exposed in Sepulveda Boulevard road cuts just east of Lower Van Norman Reservoir in the Mission Hills. These faults are probably related to both the San Gabriel and the Sierra Madre fault systems. The most southerly of these fault planes is a 60 degree south-dipping reverse fault with rocks of the Modelo Formation on the north limb of the Pacoima Hill anticline thrust over the lower Pliocene Repetto Formation. The next fault north dips 55 degrees south and has thrust Repetto sandstone over fossiliferous sandstone of the middle Pliocene lower member of the Pico Formation. The most northerly of the group is a normal fault dipping 75 degrees north, with upper Pliocene beds down dropped.

Pacoima Hills fault. A well-exposed east-trending normal fault dipping 50 degrees north in the Pacoima Hills has brought Basement Complex up on the south side against sedimentary and volcanic rocks of the Topanga Formation. Four miles east in the Verdugo Mountains, these formations are in unconformable contact. Displacement along this fault may be small. Bailey and Jahns (1954) projected this fault 5 miles east as a buried extension along the south side of Tujunga Valley. However, the most reasonable structural section shows no necessity for a Tujunga Valley fault (Oakeshott, 1958).

*Raymond fault.** The Raymond fault separates the Topanga Formation in the northern upthrown block from the Modelo Formation in the south block. It is mostly concealed by the older alluvium along York Boulevard, but evidence of its approximate location is given by outcrops near the fault zone. This fault is very likely a high-angle reverse fault, as shown by overturned beds in the Topanga Formation along the Arroyo Seco.

Eagle Rock fault. The Eagle Rock fault separates the Basement Complex rocks to the north from the Topanga Formation to the south. It is a vertical or high-angle reverse fault with the north block up (Weldon, 1955). No alluvium has been displaced by the Eagle Rock fault, indicating that movement on this fault stopped before movement stopped on the Raymond fault. The questionable extension of the Eagle Rock fault westward to the Verdugo fault is based on a steplike difference in ground water level in the mouth of Verdugo Canyon. The general structural pattern also suggests that the Eagle Rock fault may be related to the Verdugo fault system.

* The Raymond fault was named by Dr. J. P. Buwalda in his definitive 1940 unpublished report on the Raymond Basin. The name "Raymond Hill fault" is used on plate 1, this bulletin. All reports on the ground water geology of the area have used the name "Raymond fault."

Effects of Faulting on Ground Water Movement

There are numerous ways in which faulting may affect the movement of ground water. Some of the more important are listed as follows:

1. Impervious rock may be brought into contact with the water-bearing series, thus reducing the underflow cross-sectional area.
2. Continuous pervious strata in the alluvium may be offset and made discontinuous.
3. Impervious gouge may be formed as a result of the grinding action during recurrent movement along the fault.
4. Repeated uplift and depression of one or both sides of a fault block may allow alternate weathering of the surface deposits with resultant formation of large quantities of impervious residual clay in the vicinity of the fault.
5. Strata may be folded or overturned so that their position is unfavorable for percolation of water through them.
6. Fault fractures may be sealed by chemical deposits.
7. Brittle material may become cracked or brecciated, thus creating a more permeable condition along the line of faulting, which will allow the zone to act as a conduit and carry water. This condition has been observed to exist to a minor extent in the vicinity of the water supply tunnels in the Verdugo subarea.

A combination of all but the first and last phenomena is believed to have resulted in the formation of an impediment along the Verdugo and La Tuna Canyon faults. Extensive research and work has been done by the Los Angeles County Flood Control District on the effect of these faults on their spreading operation of water from Hansen Dam (Thayer, 1945).

Folding

In the San Fernando Valley, regional dips of the sedimentary formations are away from the pre-Cretaceous crystalline rocks which form the mountains around the valley. Unconformities between the successive Cretaceous, Tertiary, and Quaternary formations show that orogenic movements took place locally at various times; but the mid-Pleistocene orogeny overshadowed all of the others in intensity. During the faulting and the accompanying folding, the crystalline rocks behave essentially as a competent block undergoing intermittent elevation with adjustments within the block accompanied by faulting, shearing, and fracturing. Around the margins of the Basement Complex, the sedimentary strata reacted according to their competence and the local intensity of the stresses applied by developing a series of discontinuous folds closely related to the faults. Commonly, local synclines are developed on the downdropped fault blocks and anticlines on the upthrown blocks.

The dominant fold structures affecting the storage and flow of underground water in the San Fernando Valley are located only along the northern border of the valley. Inasmuch as the other folds have little or no effect on the ground water, no extensive study was made of them.

The Little Tujunga syncline (figure 1), located between the Verdugo Mountains and the San Gabriel fault, is one of the principal structural features along the north edge of the valley. The axis of this fold closely parallels the trace of the Sierra Madre fault zone, following it with a west-northwest trend in the area from Tujunga to the Veterans Administration Hospital at Pacoima Canyon, where it has been overridden by the crystalline rocks along the Hospital fault.

The Verdugo Mountains, Pacoima Hills, and Mission Hills comprise the remnants of an elevated, faulted anticlinal block trending north 75 degrees west across the northern part of the valley. Structurally, the highest part of this block is in the central part of the Verdugo Mountains, where granitic rocks are exposed. This anticlinal structure is flanked by the Topanga and Modelo Formations and plunges westward to the vicinity of Hansen Flood Control Dam. It is faulted up to expose granitic rocks and the Topanga Formation in the Pacoima Hills, and plunges west an estimated 8600 feet in the next 4 miles (Oakeshott, 1958).

The most prominent fold of the Mission Hills is the east-trending Mission Hills anticline just south of Lower Van Norman Reservoir, which exposes diatomaceous shale of the Modelo Formation at the southeast end of the reservoir. This fold may be the result of drag on the Mission Hills thrust fault. The strong westward plunge of this structure is indicated by Repetto, lower Pico, and upper Pico beds which successively overlie exposures of the Modelo Formation on the north and south limbs of the anticline.

Geophysical studies of nonwater-bearing rocks in the western portion of the San Fernando hydrologic subareas made by various oil companies show a series of three synclines with two intervening anticlines that have an easterly plunge in the nonwater-bearing rocks. This structure is somewhat simpler than was originally postulated by Eckis in California Division of Water Resources Bulletin 45 (1934).

QUATERNARY GEOLOGIC HISTORY

The rise of the San Gabriel Mountains and other ranges and hills was accelerated during early Pleistocene time. The water-bearing Saugus Formation (including Sunshine Ranch Formation, Oakeshott, 1958) is represented by fluviatile and alluvial fan sediments derived during the early Pleistocene from the then existing San Gabriel Mountains. The sediments from the San Gabriels merge into marine sediments derived from the Santa Susana Mountains to the west. There is no evidence of a similar deposit along the base of the Santa Monica Mountains, indicating that during Saugus time this portion of the area was undergoing erosion.

The mid-Pleistocene orogeny was the major event in building the modern mountain ranges and hills around the perimeter of the valley. At that time, the Saugus and all older formations were intensely folded, and large movements took place in the San Gabriel and other fault zones at the northern edge of the valley. The Santa Monica Mountains, Simi Hills, and Santa Susana Mountains were elevated with the latter two cutting off the San Fernando Valley from the Ventura Basin. The major streams accelerated their erosion and incised deep canyons in the mountains. Some of the first products of post-Saugus erosion are represented in the dark brown and reddish fanglomerate of the Pacoima Formation (Oakeshott, 1958). Strata of this formation have been locally folded in and near fault zones, particularly in the fault zone west of the Veterans Administration Hospital north of San Fernando.

Post-Saugus erosion of the higher lands has continued through upper Pleistocene to the present time. Erosion during this time has been modified, accelerated, or interrupted by repeated elevation of the mountain masses. A succession of terraces produced by deposition from the various streams has been developed and then incised or eroded as the stream gradient has been modified. Most of the terrace deposits parallel present drainage courses, indicating that they were left by these same streams in earlier cycles of erosion.

Erosion and elevation of the land mass has continued to the present time. The alluvial fill during this time has been derived from two types of material, which have had a profound effect on the permeability of the aquifers and on the quality of the water. West of the vicinity of Van Norman Reservoir complex and along the southern portion of the valley, local streams from the hills have deposited debris from predominantly sedimentary rocks of that region forming relatively tight deposits that have low specific yields. East of the Van Norman Reservoirs, the streams of the Pacoima, Little and Big Tujunga, Verdugo, and other drainages along the northern edge of the valley have formed alluvial fans consisting almost entirely of coarse crystalline debris of high specific yields from the San Gabriel and Verdugo Mountains.

The coalescing alluvial fans from the major tributaries to the north have forced the Los Angeles River to the southern margin of the San Fernando Valley.

GEOLOGIC CONDITIONS AFFECTING OCCURRENCE AND MOVEMENT OF GROUND WATER

Geologic conditions, along with the supply and disposal of water itself, control the occurrence and movement of ground water in the Upper Los Angeles River Basin. Features such as faults, folds, and lithologic variations have a pronounced effect on the elevation of the ground water surface and the direction of ground water movement.

The source of ground water supply to the hydrologic subareas is infiltration of direct rainfall, surface runoff from adjacent hill and mountain areas, artificial spreading of surface runoff and imported waters, and a minor amount of underground percolation of water from the mountain masses to the alluvium. Outflow of the supply is by pumping for man's consumptive use, export, surface runoff, and by underflow of small amounts out of the area through the Los Angeles Narrows.

The Basement Complex, the pre-Quaternary sediments, and the volcanic rocks which underlie the study area at depth are relatively impervious; and any contribution of ground water from them is probably small. The investigation has revealed no evidence of

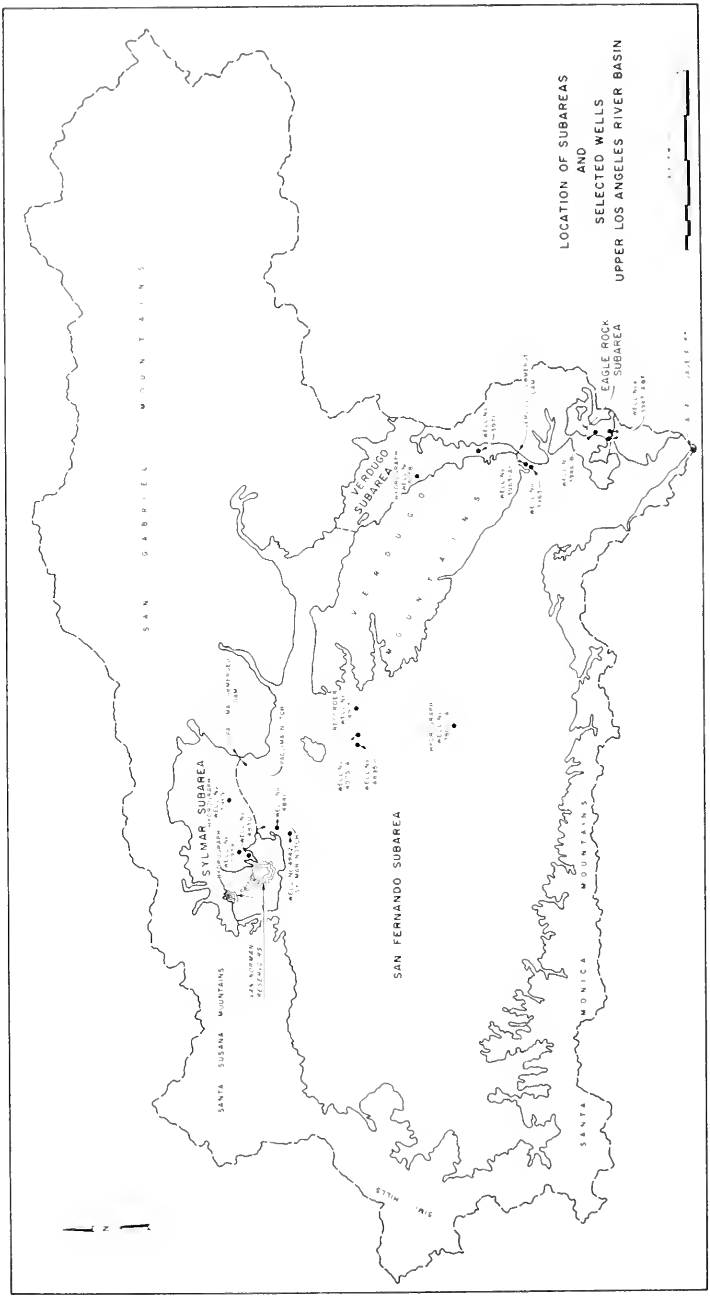


Figure 2. Location of subareas and selected wells, Upper Los Angeles River Basin.

subsurface outflow other than through the Los Angeles Narrows.

San Fernando Hydrologic Subarea

All but about 9 percent of the upper Los Angeles River ground water basin is included in the San Fernando hydrologic subarea. The subarea is readily divided into eastern and western units on the basis of the type of alluvial fill in each unit. The valley fill of the western portion of the area is essentially fine-grained material derived from the surrounding sedimentary rocks. These fine-grained materials transmit water at a relatively slow rate, whereas the coarse-grained detritus of the eastern portion of the subarea transmits water at a relatively fast rate. The coarse-grained detritus, with high permeabilities and high yields, has been eroded mainly from the granitic Basement Complex. The deposits are essentially sand and gravel with some fine material in the interstices; in places, boulders up to 3 feet in diameter are relatively common. The ground water storage capacity of the coarse deposits of the eastern unit is much greater than that of the fine deposits in the west. In fact, about two-thirds of the ground water in storage in the San Fernando hydrologic subarea lies beneath the eastern third of the surface area.

Western portion. In the northwestern portion of the subarea, a prominent fault extends northeastward from the vicinity of Chatsworth Reservoir, crossing Topanga Canyon Boulevard and Devonshire Street in the valley fill (figure 1). This fault has displaced the nonwater-bearing materials forming a steep ground water gradient on the order of 80 feet in height. The area is underlain at shallow depths by Cretaceous sandstone northwest of the fault and the Modelo shale at greater depth south of the fault.

The Northridge Hills fault forms a barrier, or partial barrier, to the movement of ground water either by offsetting permeable beds or by bringing less permeable materials closer to the surface. The exact difference in water levels across the fault is not known. To the east, the upper portion of the fault has presumably been removed by erosion by the combined action of Pacoima and Tujunga Creeks.

The small arcuate fault shown west of the intersection of Balboa Boulevard and Ventura Boulevard has had no known effect on the movement of ground water. The existence of this fault is based primarily on the apparent vertical offset of the upper member of the Modelo Formation that crops out on the north side of the fault.

Ground water is nearer the surface in the western portion of the hydrologic subarea. This area is bounded on the east by Reseda Boulevard, on the south by the Los Angeles River and to the west by Topanga Canyon Boulevard. The northern boundary is somewhat irregular, extending north of Roscoe Boulevard near Reseda Boulevard. This area was studied in detail by the U.S. Department of Agriculture, Soil Conservation Service, during the period 1947 through 1950 (Donnan *et al.*, 1950). Their investigation pointed out the following conclusions:

> Water level fluctuations recorded by the piezometers installed by the Soil Conservation Service were cyclic with precipitation; these water levels also responded to irrigation water applied in excess of the consumptive use; and deep artesian and/or pressure wells within the area leaked into the shallow zone to the extent that small ground water mounds were developed around certain wells. The source of the confined water appears to be aquifers in the Saugus Formation. The Saugus Formation presumably underlies the alluvium at relatively shallow depths. These aquifers are recharged by precipitation on the surface exposure of the Saugus Formation to the north.

Ground water under pressure in the western portion of the subarea is in small localized gravel lenses confined by clay strata.

Eastern portion. The over-all permeability of the alluvial-fan deposits below Hansen Dam has been reduced by faulting. Gravel beds displaced by thin clay seams in the fault planes have been observed at the 130-foot level in the Arrow Rock Products gravel pit south of well 4916-B. These sheared gravels do not represent the main trace of the Verdugo fault; however, they illustrate how the associated faults may act as partial barriers to the movement of ground water.

There are two marked breaks in the ground water surface in this area. The first essentially underlies Hansen Dam and appears to be a steep ground water gradient over the north-dipping Modelo sandstone on which the dam is founded and into the upper portion of the area near the gravel pits. A well, located about 1000 feet south of Hansen Dam, and the exploratory drill holes for the dam (La Rue, 1943) indicate that nonwater-bearing rocks are at about 900 feet elevation, whereas approximately 10,000 feet south of Hansen Dam near the Verdugo fault zone the base of the water-bearing rocks is about 600 feet deeper, lying between elevation 200 and 300 feet above sea level. The second break in the ground water surface is at the Verdugo fault. On January 20, 1945, there was a 75-foot difference in the elevation of the water table observed between wells 4895 and 4905-A. These wells straddle the Verdugo fault and are 3000 feet apart. The difference in ground surface elevation between the wells is 28 feet. Considering the high permeability of the aquifers tapped by these wells and the lack of heavy draft in the area, a water table with an over-all slope of 150 feet per mile, about 2½ times as great as the surface slope, seems improbable when compared to the normal water table slope in the northern part of San Fernando Valley. The normal slope of the water table in these sediments is about 15 feet per mile or about a third of the surface slope. These facts alone warrant the assumption that the Verdugo fault zone is at least a partial barrier to the movement of ground water. Observations of this condition were initially reported by Warren N. Thayer (1945) of the Los Angeles County Flood Control District.

Between the southeastern corner of the Mission Hills and the southwestern side of the Pacoima Hills, there is a very sharp difference in the ground water surface of approximately 250 feet. This discontinuity in water levels is discernible between wells 4841 and 4842. It is assumed that this feature is caused by a difference in the elevation of the underlying nonwater-bearing materials. Very little is known about this feature because of the lack of well data in the vicinity.

Another difference in ground water levels is present in the Sunland area adjacent to Tujunga Wash. This difference apparently is due to faulting in the nonwater-bearing rocks with the water surface being about 50 feet lower on the northwest, Tujunga Wash side of the feature.

A steplike water surface is present below the submerged Verdugo dam of the City of Glendale. The submerged dam is located beneath the City of Glendale Verdugo Recreation Area. The steps in the water surface are due to the offsets in the Basement Complex along the Verdugo fault zone. No surface evidence of any faults that might form a barrier to the movement of ground water has been found. The water surface elevation at Verdugo well 3963-A is generally about 90 feet higher than well 3963, which is located about two-thirds of a mile downstream; and the water levels at a well two-thirds of a mile farther downstream are 250 feet lower yet.

The water-bearing rocks of the Los Angeles River Narrows are very permeable. The City of Los Angeles has two well fields in the area. Because of heavy pumping, large depressions have been created in the ground water surface. The largest of these pumping depressions is at the large bend in the Los Angeles River where the river begins its southerly course through the Narrows. This well field and nearby wells immediately north have created a pumping depression.

The historic rise of water at the lower end of the upper Los Angeles River basin is due in part to the reduction in the cross-sectional area as the stream approaches the Los Angeles County Flood Control District F-57 gage. The maximum depth of water-bearing rocks near Figueroa Street (Gage F-57) is about 110 feet, whereas the maximum depth at the Pollock well field near Fletcher Boulevard is 260 feet.

Rising water has been noted in the past in the vicinity of Los Feliz Boulevard, about 3.5 miles upstream from the primary area of rising water. This was probably due in part to a constriction or reduction of the cross-sectional area of water-bearing rocks. The constriction is caused by the small buried hill of nonwater-bearing rock just downstream from Los Feliz Boulevard.

Movement of ground water. The slope of the water surface and direction of ground water movement in the unconfined zones of the San Fernando hydrologic subarea is generally to the east toward the Los Angeles River Narrows.

The ground water in general moves away from the surrounding hills and mountains to percolate into the permeable portions of the alluvial fans.

Sylmar Hydrologic Subarea

Formations. The nonwater-bearing rocks that form the northern boundary of the subarea are composed essentially of Basement Complex; however, in the northwestern portion of the area, rocks of the sedimentary Repetto Formation are faulted against the Basement Complex. The Repetto Formation also occurs along the southeastern boundary and again in the Mission Hills, where it is overlain by a thin section of nonwater-bearing Pico Formation.

The water-bearing deposits in the Sylmar subarea consist of the Saugus Formation, older (Pleistocene) alluvium, and Holocene alluvium. The Saugus Formation is about 6400 feet thick and is composed of strata that vary greatly in permeability. Some members of the formation make good aquifers while others are aquitards. The older alluvium may be a maximum of 300 to 500 feet thick west of the Veterans Administration Hospital, in the northeastern portion of the subarea. These materials are composed of coarse detritus derived from the Basement Complex; however, in some places residual clay has developed as a result of weathering. The Holocene alluvium attains a thickness of 50 to 60 feet in Pacoima Wash where the erosive action of the stream has incised the water-bearing units and then backfilled the eroded area with very coarse granitic debris. In the remainder of the subarea, where Holocene alluvium occurs, it constitutes only a thin veneer on top of Pleistocene older alluvium and Saugus Formation.

Structure. The geology of the Sylmar subarea is greatly complicated by faulting and folding. The nonwater-bearing rocks materials to the north of the subarea have been faulted and in part thrust southward over portions of the water-bearing Saugus Formation. The compressive forces that are related to the thrust faulting are also related to the formation of the Little Tujunga syncline, the most important structural feature of the subarea. At least 6000 feet of Saugus Formation and an even greater thickness of older nonwater-bearing sediments have been folded into an asymetric syncline with the north limb overturned. This syncline has been truncated by erosion and covered by a veneer of Pleistocene older and Holocene alluvium. The southeastern boundary of the subarea was first believed to have been formed only by the steep, north-dipping beds of the nonwater-bearing Repetto Formation that is part of the same synclinal structure. However, the surface breaks accompanying the February 9 earthquake show quite clearly that this boundary of the subarea is a fault.

Field investigation. Within the section between Foothill Boulevard and Mission Hills, there is a very marked discordance in water levels. In order to locate more accurately the break in the water surface, 20 bucket auger holes were drilled in 1959. Nine of the 20 holes were drilled by the City of San Fernando, five by the City of Los Angeles, and the remaining six by the State Water Rights Board. Representatives of the Board were present at the drilling of all holes and prepared detailed logs of each boring. The logs from the drilling program were used to construct a peg model which aided the analysis. The boundary of the subarea was delineated on the basis of water levels between Sylmar notch and Pacoima notch. The analysis of available water level data, data obtained from the test holes, and the geology of the area as determined during the San Fernando Reference Study indicated the following:

1. Water levels northwest of the break in the water surface were about 50 feet higher than those to the southeast of the break.

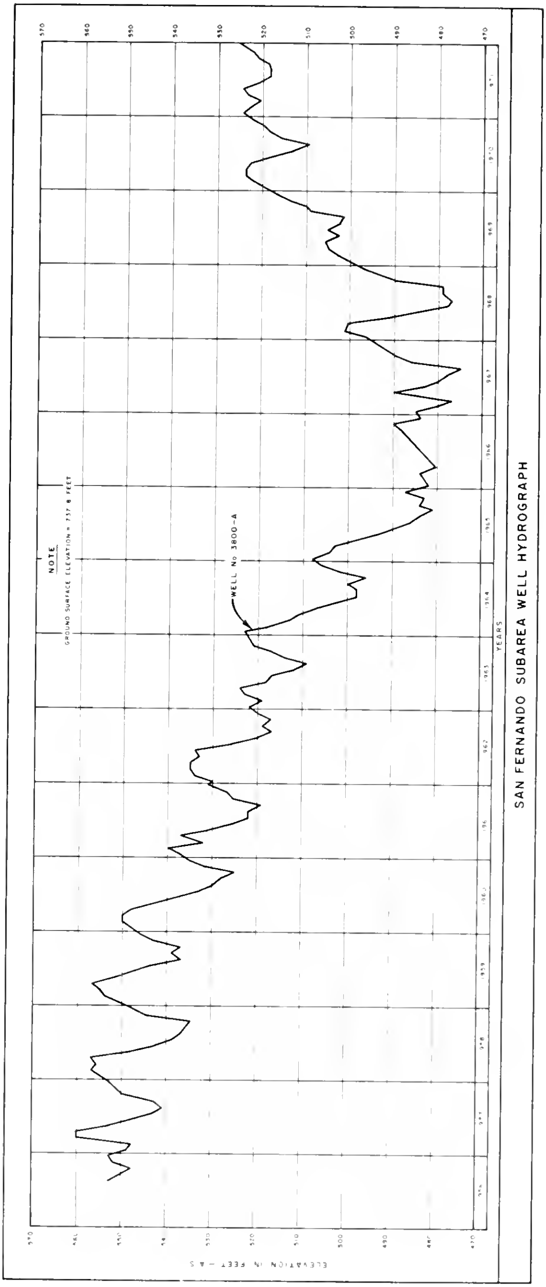


Figure 3. Hydrograph of well in the San Fernando subarea.

2. Water levels northwest of the break were considered to be related to the eroded ends of confined aquifers in the Saugus Formation.

3. Water levels southeast of the break were considered to be free ground water levels in coarse alluvial deposits which have the Pacoima drainage as a source area.

4. The discordance in water levels is related to the eroded south flank of the Little Tujunga syncline which has been covered with a thin veneer of alluvium.

5. Subsurface flow from the Sylmar subarea to the San Fernando subarea has been found only at two places; namely, the Sylmar and Pacoima Notches. There is hydraulic continuity between the confined aquifers and the veneer of alluvium that overlies the eroded south flank of the Little Tujunga syncline.

6. Continuity exists between the Sylmar and San Fernando subarea through the saturated alluvium in the two notches.

7. The configuration of the break in water surface through the Sylmar and Pacoima Notches was considered as not being sharp enough to be caused by a fault but was still a steep gradient.

These conclusions were subsequently modified by the occurrence of the zone of ground rupture related to the February 9, 1971, earthquake, indicating that faulting was involved.

Occurrence and movement of ground water. The information obtained from the test holes drilled in 1959 greatly aided the understanding of the occurrence and movement of ground water within the subarea. The noticeable pressure rise of the water surface which took place in several of the test holes during and immediately after drilling, coupled with the fact that there are historic records of artesian flows for the Mission well field and the City of San Fernando well field, indicate that a confined water system exists within the Sylmar subarea. The test drilling indicated that a free ground water area of limited size is present between the two well fields. All wells in the subarea derive their water supplies from the confined aquifers of the Saugus Formation. In 12 of the 20 test holes, Saugus Formation was encountered and partially penetrated before saturated materials were reached.

There is a decline in water level in the free ground water area in the Sylmar subarea coincident with heavy pumping of the Mission well field. Therefore, on the basis of the period of record available, it is concluded that the free ground water area is in hydraulic continuity with the confined aquifer.

The Sylmar and Pacoima Notches are the principal areas of subsurface escape from the subarea. The slope of the ground water surface through the Sylmar Notch suggests that small quantities of water are flowing over a relatively impermeable lip or barrier. Data on the slope of the ground water surface through the Pacoima Notch are not available.

The exact location and extent of the forebay or recharge area for the confined aquifers are not definitely known; however, the permeable alluvial deposits in Pacoima Wash are in a favorable position to recharge the dipping aquifers of the Saugus Formation that are in contact with the stream gravels in the incised and backfilled portion of Pacoima Wash. These permeable deposits act as a sponge, holding water for release into the aquifers of the Saugus Formation. Ground water contours indicate that there is a downward slope of the water surface from Pacoima Wash toward the lower portion of the subarea where the majority of extractions are made. Routing studies made by the staff of the Water Rights Board on the Sylmar subarea indicate that the water supply from Pacoima Creek that could remain in the water-bearing materials above the Pacoima submerged dam would not be sufficient to maintain the water levels in the area through a normal period of wet and dry years. Deep percolation of precipitation and applied water and of runoff from hill and mountain areas are also major sources of recharge. Such recharge is believed to percolate through the alluvial blanket and enter some of the truncated aquifers of the Saugus Formation.

The hydraulic gradient under static conditions indicates that it is improbable that Lower Van Norman Reservoir has contributed water to the subarea in the past. Records of well 4830, about 2,000 feet east of the reservoir, show that water levels have dropped below elevation 1,120 feet (high water surface of Lower Van Norman Reservoir) only six times between 1932 and 1954. Under pumping conditions, the water levels are lowered about 90 feet and a favorable gradient toward the well could be developed in various aquifers between the Mission well field and the Lower Van Norman Reservoir. However, the available information is insufficient to support a conclusion that flow occurred while the well was being pumped.

It is possible that ground water can move westward in the Saugus Formation from the vicinity of Kagel and Lopez Canyons which lie immediately to the east of Pacoima Wash, since a favorable hydraulic gradient exists and the synclinal structure of the Saugus Formation plunges westward. The amount of water that could be derived from the Kagel-Lopez area would be relatively small since the area of tributary drainage adjacent to the permeable formation is small. Wells located in the upper Kagel Canyon area, penetrated approximately 900 feet of the Saugus Formation. Since the yields of these wells are very poor and water levels are declining, it may be inferred that ground water is being mined.

Since the recharge from the Pacoima Wash area, coupled with deep percolation of precipitation and delivered water on the remaining surface of the subarea, appears to have been of sufficient magnitude to maintain water levels at their historic levels, historic recharge from Lower Van Norman Reservoir or Kagel and Lopez Canyons is improbable.

Water level fluctuations within the eastern portion of the Sylmar subarea are represented by hydrographs of wells 5939 and 5969, which are shown on figure 4. Water levels in the lower portion of the subarea have declined about 80 feet below the 1944–45 high-water levels.

Verdugo Hydrologic Subarea

The water-bearing materials of the Verdugo subarea are surrounded by a complex of granitic and metamorphic rocks which have been highly fractured. Miller (1934) mapped the rocks in two main groups, the Wilson Diorite and the San Gabriel Formation. The Basement Complex yields only small amounts of water to springs and tunnels from fracture systems

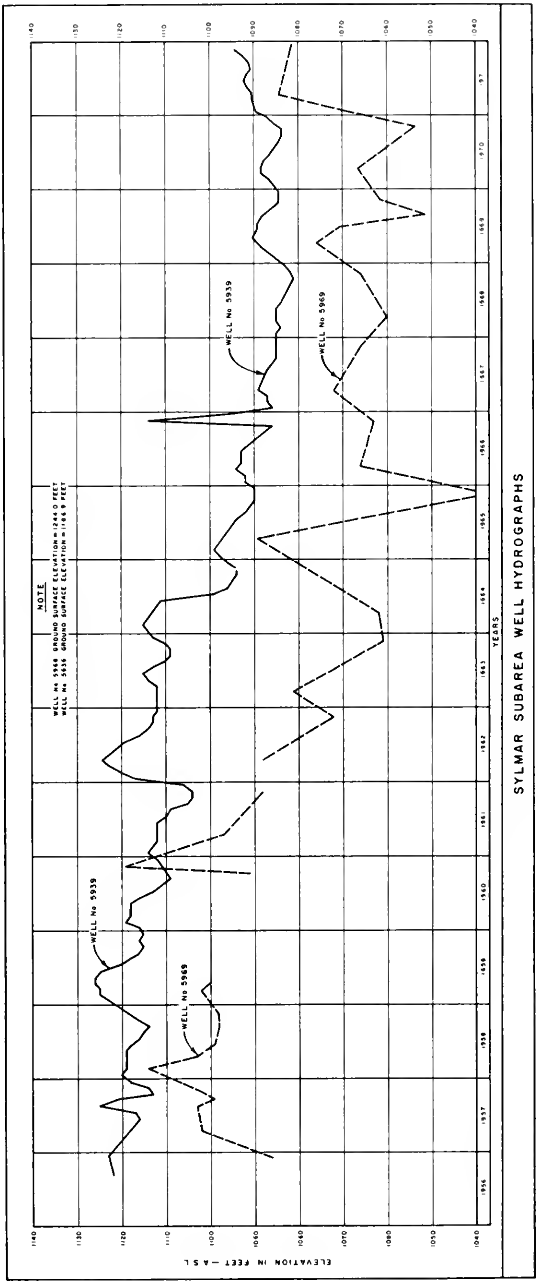


Figure 4. Hydrographs of wells in the Sylmar subarea.

which in turn are supplied by infiltration of precipitation. The over-all average flow from each of these tunnels and springs has been estimated to be about 20 gpm.

The valley fill is composed essentially of coarse detritus that has been deposited in a series of coalescing fans. The principal source area has been the San Gabriel Mountains. Well logs indicate a fairly high content of sand, gravel, and boulders, as well as considerable clay in the matrix of some of these materials. Since material in the area north of Foothill Boulevard has a lower specific yield, wells in this portion of the basin have much lower production than wells lower in the valley.

A series of cross-sections and bedrock contours drawn through the subarea indicate that the elevation of bedrock decreases toward the southeast in the La Cañada-Pickens Canyon area and that a buried ancestral Pickens Wash slopes southwest. Available ground water level measurements indicate that the ridge obstructs the flow of ground water from the northeast to the Verdugo subarea under low water-table conditions such as those of the fall of 1958; however, the water was above the ridge in such high water-table years as 1944.

Geologic studies do not indicate that there are any sources of ground water entering the Verdugo subarea from outside the watershed along faults or fracture systems.

Direction of ground water movement. The ground water in the Verdugo subarea moves southward from the mouths of canyons in the San Gabriel Mountains toward Verdugo Canyon.

Water level fluctuations within the Verdugo subarea are represented by the hydrograph in figure 5.

Eagle Rock Hydrologic Subarea

The Eagle Rock subarea is in the eastern portion of the Los Angeles River drainage basin adjacent to the Los Angeles River Narrows. The surface drainage flows generally towards the vicinity of Eagle Rock Boulevard, then southwest to the Los Angeles River. The total tributary drainage of the area above the Raymond fault and its intersection with Eagle Rock Boulevard is about 2910 acres.

The subarea is an artesian basin in which all present-day pumping is at the lower end of the pressure area.

Formations. Topanga and Puente (Modelo) Formations are the principal nonwater-bearing rock units cropping out in the area surrounding the water-bearing rocks, although highly fractured Basement Complex is present in the hill area to the north.

The water-bearing materials are composed essentially of older alluvial deposits (Pleistocene) of sand, gravel, and considerable clay. Holocene alluvium constitutes only a thin veneer along the stream channels.

The Eagle Rock and Raymond faults are the main fault features of the area. The Eagle Rock fault separates the Basement Complex to the north from the Topanga Formation to the south and is a vertical or high-angle reverse fault with vertical movement of several hundred feet. No alluvium has been displaced by the Eagle Rock fault (Weldon, 1955).

The Raymond fault separates the Topanga formation in the northern upthrown block from the Puente Formation in the south block. The trace of the fault is concealed by the older alluvium along York Boulevard, but an approximate location is indicated by outcrops near the fault zone. There is no surface indication that movement on the Raymond fault has affected the older alluvium; however, some movement must have occurred prior to the deposition of the gravelly aquifer materials to cause the change from the essentially fine-grained materials of the lower aquitard. It is quite probable that traces of such movement have been buried during the deposition of the upper aquitard material.

Occurrence and movement of ground water. A detailed study of well logs, water level data, and geology has led to the conclusion that a simple artesian basin exists in the Eagle Rock subarea. The lower end of the aquifer abuts against the Raymond fault and the nonwater-bearing Puente Formation. The pressure area extends northward toward Colorado Boulevard.

Because of a lack of data in the upper portion of the pressure area and in the forebay, an accurate determination of the extent of the pressure area cannot be made at this time. However, it is estimated that the pressure area has an area of approximately 250 acres and the forebay has an area of about 530 acres. Based on a pressure area of 250 acres, a thickness of 10 feet, and a specific yield of 19 percent the storage in the pressure aquifer is estimated to be 475 acre-feet. All wells located within the assumed pressure area have had a record of artesian flows.

Study of the U.S. Department of Agriculture Soil Survey of the Los Angeles area, California, 1919, indicates a long, narrow area of Chino clay loam extending northward in the vicinity of Eagle Rock Boulevard. This soil probably supported both phreatophytes and hydrophytes. The water to sustain the plants would represent the overflow from a full pressure aquifer. If the aquifer were full and had no additional capacity for storing water, additional water flowing into the forebay would remain outside the confining layer or aquitard. Withdrawal of water from the confined aquifer would create available storage.

The Eagle Rock artesian system is supplied with water by percolation of runoff and of applied irrigation water.

Direction of ground water movement. Ground water in the Eagle Rock subarea moves southward. There is no known subsurface escape of ground water from the pressure aquifer. The Raymond fault appears to be an effective barrier to ground water movement in this subarea.

SAN FERNANDO EARTHQUAKE

The following discussion concerns the relationship between the surface faulting that occurred as a result of the February 9, 1971, San Fernando earthquake and (1) the previously discussed boundary between the Sylmar and San Fernando subareas and (2) the performance of certain water wells in the vicinity of San Fernando during and after the earthquake.

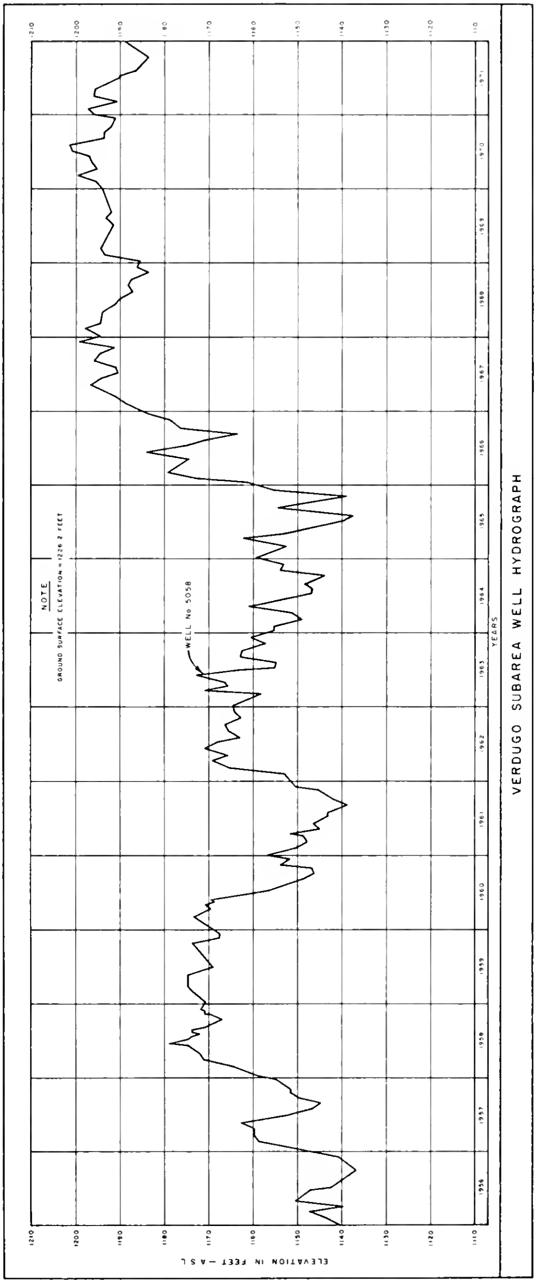


Figure 5. Hydrograph of well in the Verdugo subarea.

A discordance in the ground water surface was noted in the area northeast of the city of San Fernando during previous ground water investigations. As stated, a series of 20 bucket-auger holes was drilled to supplement the available water-well data. The line representing the break in water surface, which was originally used as the boundary between the Sylmar and San Fernando subareas, closely fits the surface faulting in the Mission Wells segment and approximates the faulting in the Sylmar segment of the 1971 San Fernando fault. The gap between the two fault segments was the area most intensively explored with bucket-auger borings and the break in water surface was most accurately determined. It is suggested that, in this area, the break in water surface be used as the inferred location of the missing fault trace (see figure 6). The greatest deviation between the trace of surface faulting and the line originally mapped occurs in the vicinity of Foothill Boulevard. However, in that area, water level data were lacking, and the break was located only by geologic judgment based on outcrops of nonwater-bearing formations located farther to the east near Pacoima Wash.

The position of the ground water surface within the Sylmar subarea has been studied to determine if a relationship exists between the depth to water and drainage from single-family wood-frame dwellings and breaks in utility lines. No such relationship was found. The Saugus Formation and older alluvium contain both confined and semiconfined ground water. Some unconfined ground water occurs in the Holocene alluvial deposits of Pacoima Wash and several other small stream channels. The Sylmar subarea is readily divisible into two parts: an eastern portion, which contains the majority of active wells, and a western portion, which contains the Van Norman Reservoirs and almost no active wells. The eastern portion is separated from the western portion by a topographic divide that extends northward from the northernmost tip of the Mission Hills (in the vicinity of the Los Angeles Department of Water and Power Olive Switching Station) to a point on the San Gabriel Mountains near Foothill Boulevard. The general direction of ground water movement in the eastern portion of the subarea is from the vicinity of Pacoima Wash southwestward toward the water wells of the City of San Fernando and of the City of Los Angeles. Some ground water moves from the direction of the San Gabriel Mountains on the north toward the same well fields. The ground water levels in the eastern portion of the Sylmar subarea generally declined from the historic highs in the early and mid 1940s due to ground water withdrawals by the City of San Fernando and the City of Los Angeles Mission well fields.

The direction of ground water movement within the western portion is toward Upper Van Norman Reservoir. The general direction of movement in the vicinity of the Juvenile Hall is from northeast to southwest.

Prior to the construction of Lower San Fernando Dam in 1913, the stream deposits in the channel section provided an avenue for the exit of subsurface water from the western part of the Sylmar subarea. Since the completion of Lower Van Norman Reservoir in 1918 and Upper Van Norman Reservoir in 1921, the naturally occurring subsurface outflow has been cut off for all practical purposes.

Ground water recharge to the Sylmar subarea is accomplished by the percolation of rainfall and runoff from the various tributary canyons, as well as the percolation of applied Owens River water. The major portion of land area within the Sylmar Basin lies within the corporate limits of the City of Los Angeles. The water supply for the City of Los Angeles, Sylmar District, is obtained from the Owens River Aqueduct. All of the pumpage from the City of Los Angeles Mission well field is exported from the Sylmar subarea to the San Fernando subarea.

Approximately three-quarters of the land area of the city of San Fernando's total of 2.3 square miles lies outside of the Sylmar subarea, yet all of the city's water supply prior to the earthquake was obtained from wells in the Sylmar subarea. Water levels in the eastern portion have declined because pumpage has exceeded the recharge from natural and imported sources. Historically, two areas of ground water close to the ground surface have been reported in the Sylmar subarea. These areas were described in testimony of the *Burr vs. Maclay* litigation (see section on "Brief history of litigation, this chapter) as being the East and West Cienegas. The 175-acre East Cienega, sometimes referred to as the Porter Cienega, was the largest. It extended from the Mission Hills in the vicinity of the present-day Mission well field to the City of San Fernando wells located near Fourth Street and Hubbard Avenue. Wells drilled in this area before the turn of the century were artesian.

The 80-acre Western Cienega was located northeast of the northeast arm of Lower Van Norman Reservoir. Prior to the construction of the freeway, and during times of high water levels in the reservoir, a small seepage pond was formed east of Sepulveda Boulevard. The seepage pond was covered by a large fill for the Golden State Freeway. The earthquake damage to the freeway in that location may be directly related to this earlier history of near-surface ground water.

Rising water from both Cienegas was diverted to Mission San Fernando for domestic and irrigation uses. These diversions constitute the earliest reported hydraulic works in the northern portion of the San Fernando Valley. The areal extent of the old Cienegas was verified by detailed pedological surveys. High calcium carbonate and high organic carbon contents were used to delineate former areas of near-surface ground water.

A third area of near-surface ground water was delineated during the investigation of ground displacement at San Fernando Valley Juvenile Hall, conducted by Fugro, Inc. Borings made after the February 9, 1971, earthquake revealed the presence of ground water at depths ranging from 6 to 30 feet below ground surface in the area of ground rupture. The materials containing the near-surface ground water are overlain by soils cemented by calcium carbonate. These soils are similar to those found in the East and West Cienegas. It is quite evident that the near-surface

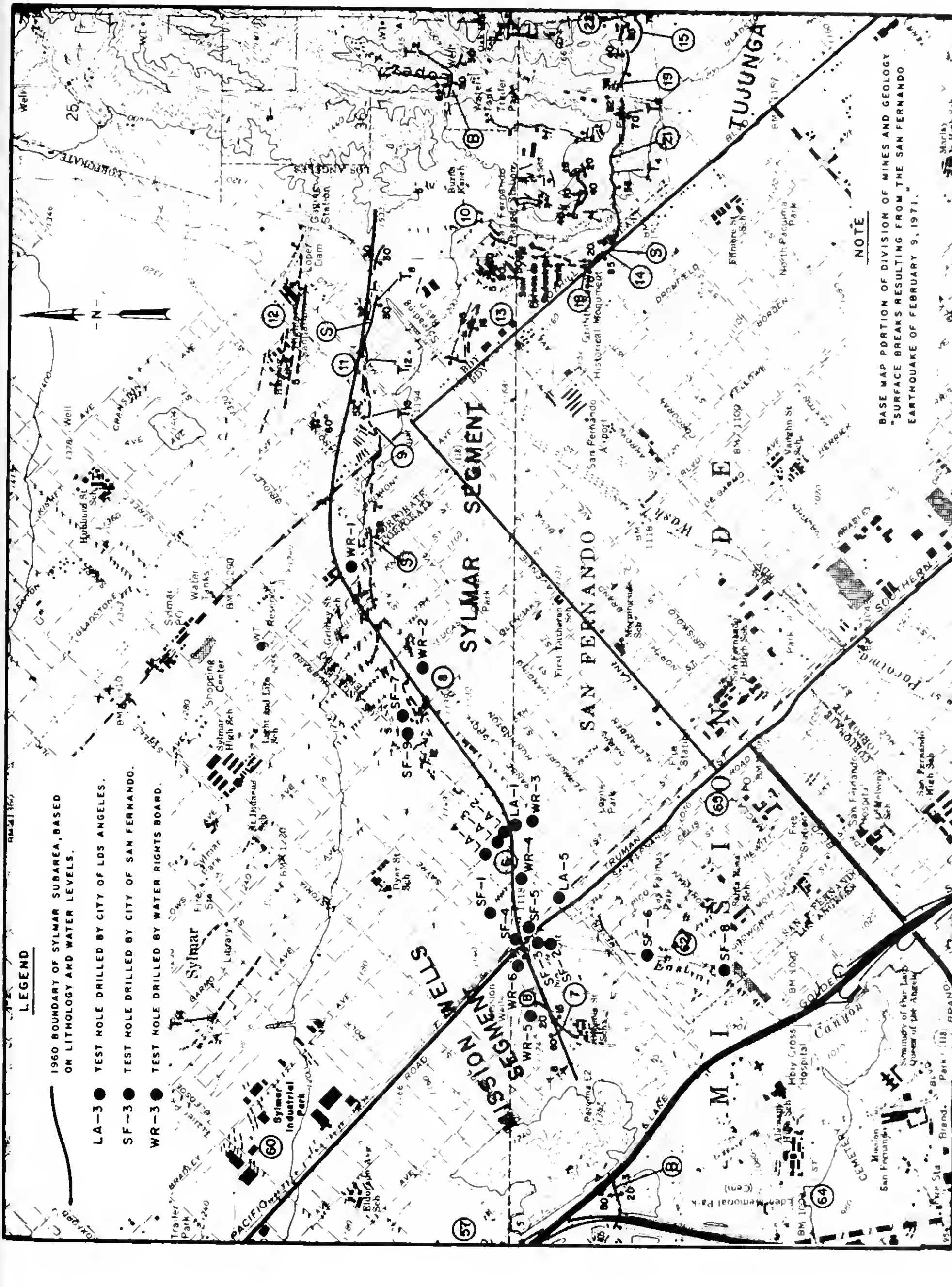


Figure 6. Relationship between surface breaks of San Fernando earthquake and boundary of Sylmar subarea.

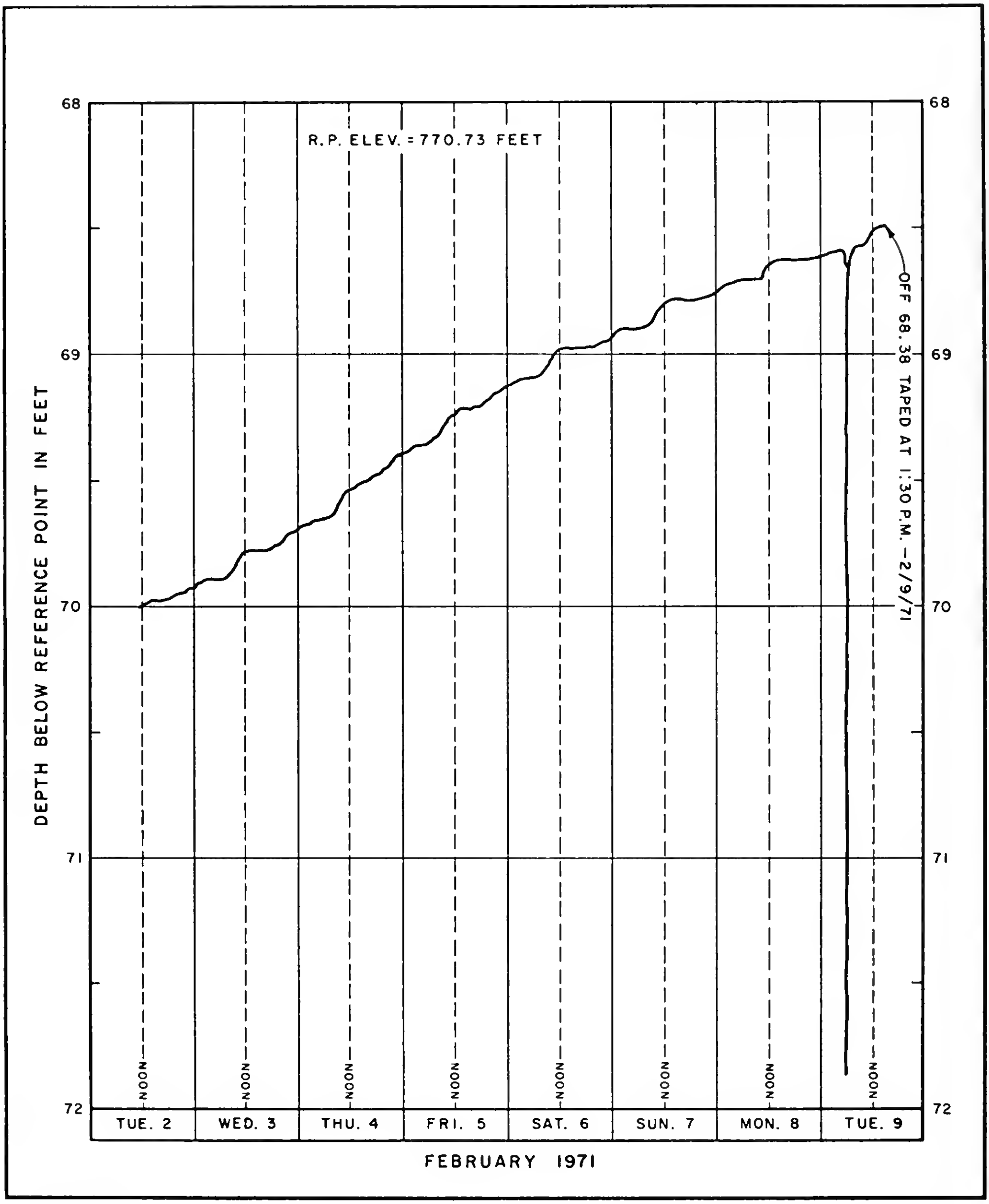


Figure 7. Recorder chart for well, showing effect of earthquake.

ground water contributed to ground rupturing at the Juvenile Hall facility and in the open field area immediately to the south. Damage to some of the fills for the Jensen Filtration plant may also be related to the near-surface ground water around Upper Van Norman Reservoir.

Performance of Water Wells

There are records and data on more than 400 water wells in the upper Los Angeles drainage basin. About 190 of the wells are owned by the City of Los Angeles. The remaining wells are those belonging to the 200+ defendants in the case *City of Los Angeles vs. City of San Fernando et al.* or their successors. The Cities of Los Angeles, Glendale, and Burbank are the largest pumpers of ground water. A recently conducted survey of the water-well owners indicates that the only water wells that suffered any noticeable damage during the February 9, 1971, earthquake were those belonging to the City of San Fernando. As a result of earthquake damage to the City of San Fernando well No. 7, and the high bacteria content in other City wells, the City of San Fernando extracted 1526.06 acre-feet less than their legally allotted amount of 2,737 acre-feet during the 1971 water year ending September 30, 1971. Emergency connections with the Metropolitan Water District feeder lines allowed the City of San Fernando to continue limited water distribution. As a result of the decreased pumping in the Sylmar subarea, ground water levels have risen.

Ground Water Level Fluctuations

The effects of ground shaking caused by the San Fernando earthquake were recorded on numerous continuous water-level recorders in southern California. Well no. 4915, located in the Consolidated Rock Products Sun Valley pit below Hansen Dam, is the closest well to the Sylmar area that was equipped with a continuous water-level recorder. This well, 3 miles south of the ground rupture along the Tujunga segment of the San Fernando fault, recorded a deflection of about 0.5 foot in the water surface during the earthquake. The water surface returned to its original level immediately after the main shock. Interpretation of the recorder chart and other well measurements by personnel at the City of Los Angeles Department of Water and Power indicates that there were no permanent changes in ground water elevations directly attributable to the February 9, 1971, earthquake. The short-term water-level fluctuation within recorder well 4915 was attributed to ground shaking and vibration of the well structure itself. The Cities of Glendale and Burbank indicated that there were no earthquake-induced effects noted in any of their water wells.

Proctor *et al.* (1972) of Metropolitan Water District suggest that, in general, water levels in observation holes north of the surface rupturing rose abruptly, then slowly subsided to near their original position. The two tables of measurements presented in the Proctor paper suggest that no clear-cut relationship exists between the pre- and post-quake measurements. Some of the differences are of such small magnitude that one might suspect differences in barometric pressure as the cause. Other measurements that indicate a rise may be related to normal seasonal fluctuations such as are illustrated on the hydrographs of wells 5939 and 5969, which were on an upward trend prior to the earthquake.

Geology of the Southeast Slope of the Santa Susana Mountains and Geologic Effects of the San Fernando Earthquake

by Richard B. Saul[1]

ABSTRACT

Sedimentary rocks of Late Tertiary and Quaternary age exposed at the north edge of the San Fernando Valley record the time, scope, and duration of episodes of folding and faulting that generated the present landscape.

In the southeast quarter of the Oat Mountain quadrangle and the adjacent part of the San Fernando quadrangle, west of the San Diego Freeway, there are three structural provinces: northern, southern, and eastern. The northern province is comprised of rocks and structures lying above the sole of the Santa Susana thrust; the southern province, the folded, faulted, and eroded rocks underlying the north edge of the San Fernando Valley; and the eastern province, the rocks and structures involved in Late Quaternary uplift of the western end of the San Gabriel Mountains, of which the San Fernando earthquake of February 9, 1971, was an episode.

Most of the surface breaks and structural damage were confined to a zone along the trace of the Santa Susana thrust, probably as a result of local amplification of ground shaking. West of San Fernando Pass, permanent ground deformation accompanying the earthquake was distributed along favorably oriented, pre-existing planes of weakness.

The Santa Susana fault probably has been inactive since the middle Pleistocene. The faults most active during the earthquake are not relatable to it in time or space. The Devonshire and Northridge Hills faults have been sites of Late Quaternary displacement.

Mapping in detail suggests that further refinement of some local stratigraphic units is needed.

This report is based on detailed geologic mapping of the south slope of the Santa Susana Mountains, in the Oat Mountain and San Fernando quadrangles. The mapped area extends eastward from Limekiln Canyon * to San Fernando Pass, southward from San Fernando Pass to the Mission Hills, and to the east shore of the Van Norman Reservoirs. It was studied originally by W. S. W. Kew (1924).

Subsequent exploration for oil in this area led to discovery of four fields, two of which continue to yield oil (Leach, 1948). The largest producing field, Aliso Canyon, is described by Hazzard (1944) and Hanson and Saunders (1962); the other field, Cascade, is described by Roth and Sullwold (1962). The two smaller, inactive fields are Horse Meadows, described by Stewart (1962) and Cordova (1965), and Mission, described by Cassell and Sanem (1962).

Following Kew's work, the principal published reports on the area are those of Oakeshott (1958), who mapped the area now covered by the San Fernando, Sunland, Mint Canyon and Agua Dulce 7½′ quadrangles; Winterer and Durham (1962), who mapped west of San Fernando Pass; and Jennings and Strand (1969), who compiled the regional geology on the Los Angeles Sheet of the Geologic Atlas of California (see plate 1, this Bulletin).

Important unpublished theses are those by Bishop (1950), who mapped from Limekiln Canyon west to the Los Angeles-Ventura County line; Jennings (1957), who worked from Limekiln Canyon east to San Fernando Pass; and Merifield (1958), who mapped from the San Fernando Pass area eastward along the front of the western San Gabriel Mountains.

The work for this report was funded, in part, through a cooperative project with the Los Angeles County Engineer and the Los Angeles County Flood Control District. In addition the author is indebted to S. H. Mayeda, William Davis, and John Weldon, engineering geologists with the Los Angeles Department of Water and Power, and to Union Oil Company for sharing their data and ideas.

Although the effects of the February 9, 1971, earthquake were sparse in this area, the rocks, the geologic structure, and the landscape yield abundant data on the distribution, sequence, and magnitude of the mountain-building process, of which the earthquake was the most recent episode. Therefore, geology is stressed in this report.

STRATIGRAPHY

Previous workers have found it convenient to group the rocks exposed in this area into two provinces: a southern province, comprised of the rocks lying south of and beneath the Santa Susana thrust fault, and a northern province, comprised of the rocks in and above the thrust. A third or eastern province, added herein, is represented by the Mission Hills and adjacent terrain (figure 1).

Rocks as old as Late Cretaceous are present at depth in the southern and northern provinces. In the part of the eastern province mapped for this report, test wells have penetrated no rocks older than Miocene; however, in the San Gabriel Mountains to the east, rocks of Precambrian age are exposed. Only the rocks exposed at the surface will be discussed in this report.

---

[1] California Division of Mines and Geology, Los Angeles

* Not to be confused with another Limekiln Canyon near the east edge of the San Fernando quadrangle.

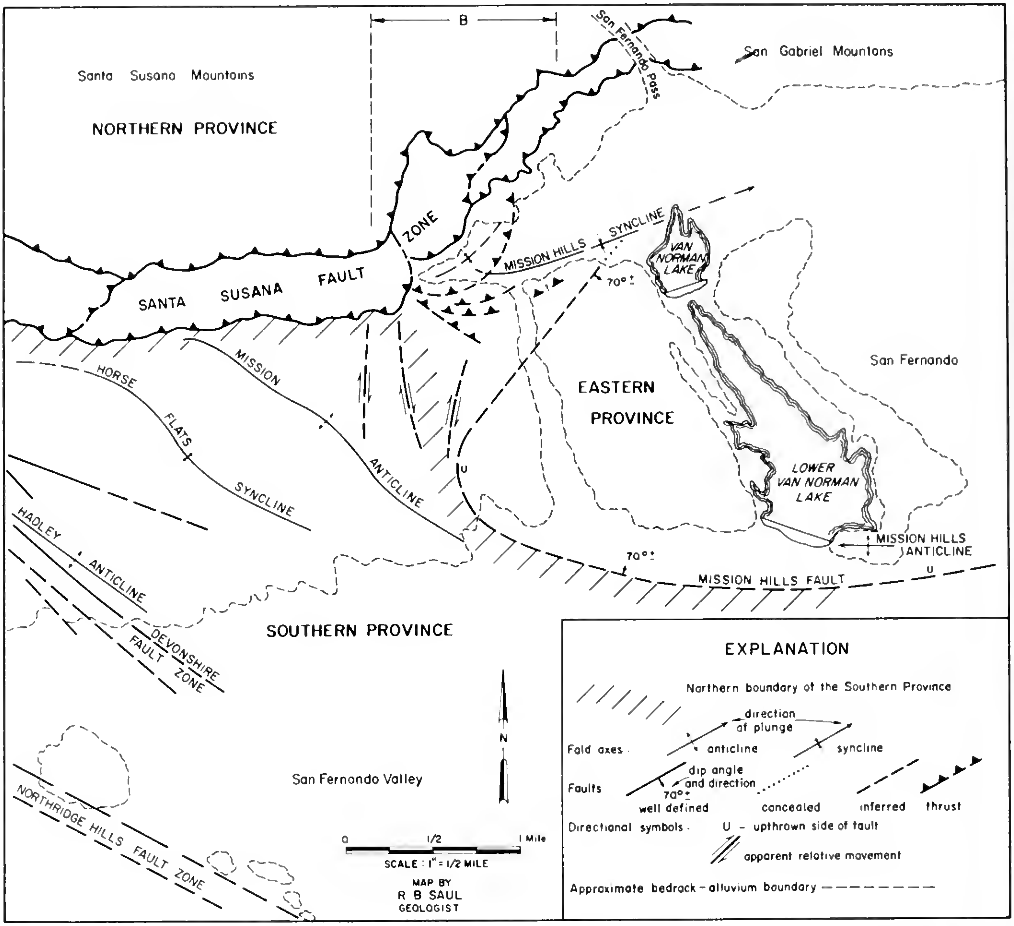


Figure 1. The three structural provinces. The space (B) at the top of the drawing marks what may be a border zone between the northern and eastern provinces. If it exists, this zone is irregular and extends at least as far south as the axis of the Mission anticline. Within and east of the zone, the east end of the northern province has become incorporated in the tectonically active eastern province. Folds and faults in both the northern and southern provinces have probably undergone continued deformation and displacement where they have become incorporated in, or lie adjacent to, the eastern province.

Northern Province

Topanga Formation. East of Limekiln Canyon, the oldest rocks exposed above the Santa Susana thrust are 244 m (800 feet) of interlayered arkosic and conglomeratic sandstone, shale, and silty shale of the middle Miocene Topanga Formation (Kew, 1924). The area of outcrop is limited to an erosional basin athwart the axis of the eastward-plunging Oat Mountain anticline at the east end of Aliso Canyon oil field. The base of the formation is not exposed here. At the type locality in Topanga Canyon, the contact with the overlying Modelo Formation is a marked angular unconformity (Susuki, 1952). At Aliso Canyon, this contact appears to be conformable and is drawn arbitrarily at the top of the uppermost sandstone unit prominent enough to include in the dominantly sandy Topanga Formation.

A brief description of the Topanga Formation is as follows, from the top down:

About 30 m (100 feet) of white and light brown, well-sorted, fine-grained, soft, quartz-rich, arkosic sandstone containing lenses of cobble conglomerate and, to the west, interbedded siltstone. The contact with the overlying Modelo Formation is paralleled by a zone of fractured, light brown sandstone 9 to 12 m (30 to 40 feet) thick.

Approximately 121 m (395 feet) of interbedded, soft gray to dark gray, light brown-weathering, arkosic siltstone, sandy siltstone, and silty sandstone. A few resistant carbonate-cemented beds.

A shale member about 18 m (60 feet) thick consisting of brown to black, light gray to brown weathering, silty clay shale bearing a microfossil fauna of the *Valvulineria Californica* zone (Luisian).

A basal sandstone member with an exposed thickness of about 80 m (260 feet) composed of white to medium gray, soft, arkosic, fine-grained sandstone.

Modelo Formation. Accurate descriptions of the stratigraphy of the upper Miocene Modelo Formation (Eldridge and Arnold, 1907) have been made difficult by large-scale thrust faulting in rocks that change facies laterally. Stratigraphically equivalent but lithologically differing rocks are juxtaposed locally in fault-bounded masses stacked up along the trace of the Santa Susana fault zone.

A rough composite section includes approximately 1036 m (3300 feet) of sediments as follows, from top down:

An upper shale member roughly 153 m (500 feet) thick that interfingers with the overlying Towsley Formation. It consists of black to gray, brown-weathering silty sand beds ranging from less than a centimeter to as much as 10 m thick. This is a soft, deeply weathered member which spalls and slakes in fresh exposures.

A sandstone member, 275 m (900 feet) maximum thickness, composed of light gray to tan, brown-weathering, generally well-indurated, fine- to coarse-grained, arkosic sandstone interbedded with subordinate amounts of shaly sandstone and silty shale. Graded beds are common; coarser grained sand generally is at the base of such beds where load casts and similar turbidite structures are apt to be present.

A shale member 183 m (600 feet) thick ranging in composition from almost pure diatomite through gray, silty, foraminiferal shale and shaly siltstone. Where best exposed, in one of the lowest thrust wedges, this member is capped by a black to dark brown, silty, clay shale unit that has lost any semblance of internal order or sequence to pervasive shearing during transport within the thrust zone. A light gray tuff bed, about 30 cm (one foot) thick, is associated with the most diatomaceous part of this member.

A member about 240 m (800 feet) thick consisting of white to light brown, porcelaneous shale and interbedded black thinly bedded fissile shale, black to brown silty clay shale, and silty sandstone. The lower third of this member is dominantly porcelaneous shale; the upper two-thirds more abundantly interbedded with the softer, less silicic beds. Silty sandstone beds increase in abundance and thickness toward the top of the member.

A 150-meter-thick (500 foot) basal member characterized by black-to-brown, silty clay shale with subordinate amounts of porceloneous shale and light gray, white-weathering, limy concretions and concretionary beds.

Near the sole of the thrust, the diatomaceous shale member lies beneath the sandstone member. In the uppermost thrust plate, on the north flank of the Oat Mountain anticline, this stratigraphic interval is occupied by porcelaneous and black-to-brown silty clay shale of the upper part of the porcelaneous shale member.

Towsley Formation. The upper Miocene to lower Pliocene Towsley Formation was described by Winterer and Durham (1954) as being characterized by coarse-grained rocks deposited by turbidity currents in deep water. Subsequently (1962), these authors stated, "The lithology and thickness of the Towsley Formation change markedly from place to place so that the designation of a section truly typical of the formation as a whole is impossible." As with the underlying Modelo Formation, additional stratigraphic confusion is found in the zone of the Santa Susana thrust.

Here the Towsley Formation is exposed through a thickness of about 610 m (2000 feet) in the crest of the Oat Mountain anticline and as a partial section in a large thrust block at the mouth of Bee Canyon. The exposed rocks are predominantly hard, light gray, light-to dark-brown-weathering, fine-grained, poorly sorted sandstone interbedded with silty, gray, brown-weathering shale and siltstone. The sandstone contains abundant structures and stratification commonly ascribed to turbidites. Some beds include abundant, dark-brown-weathering concretions. Conglomerate, though generally subordinate, is relatively more abundant in the upper half of the section. The rocks in the fault block at the mouth of Bee Canyon appear to be part of the lower half of the section.

Pico Formation. Exposures of the Pliocene Pico Formation (Kew, 1924) are confined to fault blocks lying between Bee Canyon and San Fernando Pass and a narrow outcrop above the Santa Susana thrust in the Pass. The base of the formation exposed in San Fernando Pass is light-to dark-brown-weathering sandstone and conglomerate of varying thickness that interfingers with the underlying, less conglomeratic Towsley Formation. In the fault zone, conglomerate, sandstone, and fossiliferous sandstone and gray siltstone are exposed. The contact with the overlying Sunshine Ranch Member of the Saugus Formation is in an overturned syncline in the Santa Susana fault zone just west of the Pass.

Sunshine Ranch Member of the Saugus Formation. In 1958, Oakeshott quoted J. C. Hazzard's unpublished use of the name "Sunshine Ranch Formation," typically exposed in the vicinity of Van Norman Reservoirs; however, Oakeshott mapped it as the upper member of the Pico Formation. Winterer and Durham (1962) treated the Sunshine Ranch as a member of the Saugus Formation. In this report, the fossiliferous beds at the base of Hazzard's "formation" are placed in the Pico Formation (fossil-bearing beds higher in the section alluded to by Winterer and Durham were not found); and the Sunshine Ranch, stripped of marine affinities, was mapped as a member of the Saugus Formation. The probable Pliocene-lower-Pleistocene age of the Saugus Formation is discussed by Oakeshott (1958), who considers the Sunshine Ranch to be late Pliocene. This age has been further confirmed by the discovery (March 1972) of a horse bone and teeth. C. A. Repenning (U.S. Geological Survey) found these to be a crushed rostrum bearing the incisors and one canine and an isolated left upper jaw tooth, probably a first molar, belonging to a middle or late Pliocene species of *Pliohippus.* The field locality (U.S.G.S. NN 19-3) is on the north edge of the axial trench of the proposed new dam in the Van Norman Reservoir complex, about 180 m (600 feet) below the top of the Sunshine Ranch Member of the Saugus Formation.

Above the Santa Susana thrust and west of San Fernando Pass, an incomplete section of the Sunshine Ranch Member of the Saugus Formation is exposed in a fault block within the zone of the thrust roughly 244 m (800 feet) wide and 460 m (1500 feet) long. Here this member is dominantly soft gray siltstone with a few thin beds of characteristic white nodular limestone, concretionary gray, coarse-grained, poorly sorted sandstone beds and subordinate amounts of light gray, moderately hard conglomeratic sandstone. A complete description of this member is included in the following section on the southern province.

Southern Province

Modelo Formation. The only exposures of the upper Miocene Modelo Formation in this province are two small adjacent bodies bounded by faults, lying within the zone of the Devonshire fault on the east side of Limekiln Canyon. These are diatomaceous shale, limy concretionary beds, earthy organic shale impregnated with petroleum, and chert. Subsurface data (Stewart, 1962) indicate that rocks of this age lie about 300 m (1000 feet) below the surface at this site with no fault evident to explain their presence at the surface; however, these rocks appear to be related to a thrust block of similar rocks exposed above the sole of the Santa Susana thrust zone between Limekiln Canyon and Bull Canyon. The nearest outcrop of the body is about 2 km (a mile) north-northeast, where Limekiln Canyon cuts the thrust at the north edge of Horse Flats. Microfossils in the diatomite of the two outcrop areas are the same age (Mohnian). This problem will be discussed further in the section on structure.

Pico Formation. The Pico Formation interfingers with the overlying Sunshine Ranch Member of the Saugus Formation. As previously mentioned, in this work, the boundary was drawn above the highest recognizable marine fossil or the lateral projection of such fossil-bearing beds. The fossils and the character of the fossil-bearing rock suggest as many as three distinct near-shore environments from outcrop to outcrop in the present discontinuous exposure. It is probable that the mapped boundary does not represent the same stratigraphic horizon through its entire length because it marks a zone of transition that was once a coast line. Furthermore, the position of the present outcrop in relation to the former coastal zone is unknown.

In this province, the upper part of the Pico Formation is exposed in the faulted and eroded axes of the Hadley and Mission anticlines. In these exposures, it is generally soft to moderately firm, white to light tan, silty to coarse-grained, locally fossiliferous sandstone; but, in an outcrop just east of Shoshone Avenue, the upper contact is drawn above a soft, gray, fossiliferous siltstone.

The exposures of the Pico Formation in the southern province represent 30 to 60 m (100 to 200 feet) of a total thickness reported (Cassell and Sanem, 1962) to be in excess of 610 m (2000 feet) in wells drilled for petroleum.

Sunshine Ranch Member of the Saugus Formation. The Sunshine Ranch Member is comprised of about 707 m (2320 feet) of nonmarine sediments of Plio-Pleistocene age. The basal 60 to 90 m (200 to 300 feet) is dominantly soft light brown-weathering sandstone and conglomerate with siltstone and interbedded claystone. The upper 275 to 300 m (900 to 1000 feet) are characterized by green-gray claystone and gray siltstone interbedded with light gray to light brown sandstone and conglomerate. Some sandstone beds contain limy concretions. Cross-bedding is common in the coarser sediments. Local unconformities and channel-fill structures are common. White nodular limestone ranging from thin discontinuous beds to solid layers more than a foot thick are sparsely distributed through the silt and clay-rich units. In the upper half of the member, the nodular limestone beds become less pure. As the upper contact is approached, increasing amounts of enclosed fine sand and silt change the color of the limestone-rich beds from white to shades of gray.

The contact between the Sunshine Ranch Member and the overlying upper part of the Saugus Formation is drawn at the base of a bluff-forming sandy conglomerate. Along the northeast flank of the Mission anticline, there is a slight angular unconformity at this contact.

Upper part of the Saugus Formation. The lower-to-middle Pleistocene upper part of the Saugus Formation is comprised of about 488 m (1600 feet) of dominantly coarse-grained, nonmarine sedimentary rocks. Some siltstone beds resemble those in the Sunshine Ranch Member; but, in general, the finer grained beds of this unit are tan or brown, and clay-sized material is less abundant. Channel and fill structures and cross-bedding are common. Some channel gravels are densely cemented by calcium carbonate. In the upper half of this sequence, rounded siltstone pebbles become common, suggesting reworking from some not-too-distant uplifted area. In the upper third of the upper part of the Saugus Formation, tan- and brown-weathering siltstone is dominant.

Throughout the Sunshine Ranch Member and in all but the uppermost 10 to 15 percent of the upper part of the Saugus Formation, the pebbles and cobbles in the coarse units consist predominantly of igneous and metamorphic rock types. At present, these rock types are exposed on the north slope of the San Gabriel Mountains and in Mint and Soledad Canyons northeast as far as the edge of the Mojave Desert. Some 60 to 90 m (200 to 300 feet) below the top of the Saugus Formation, cobbles and pebbles of igneous and metamorphic rocks dwindle essentially to zero through a section 10 to 20 m (30 to 65 feet) thick. They are gradually replaced by reworked sandstone concretions and ever more angular fragments of porcelaneous shale, rocks common in the Towsley and Modelo Formations now exposed to the north in the Santa Susana Mountains (photo 1). Through the above transition, beds of coarse clastic debris become proportionately dominant over the interbedded, tan siltstone that is otherwise so predominant in the upper third of the upper part of the Saugus Formation. In addition, angular fragments of porcelaneous shale become essentially the only reworked rock type in the coarse clastic beds.

The upper 15 to 20 m (50 to 65 feet) of the shale-fragment-rich beds at the top of the Saugus Formation are thick, cliff-forming, debris-flow breccias cemented by caliche (photo 2). Although they contain local unconformities in the form of channel-fill and scour-fill structures, layering is parallel to that in the Saugus Formation of which they are the upper part. Bishop (1950) estimated a thickness of 198 m (650 feet) for the shale-fragment-rich upper beds of the Saugus Formation west of the area. Jennings (1957) suggested a thickness of 92 m (300 feet) in Limekiln Canyon.

Terrace deposits. Quaternary terrace deposits related to the erosion of the present topography lie on ridge crests and slopes along Limekiln and Aliso Canyons and beneath the level area along the axis of the Horse Flats syncline at Horse Flats. The terrace deposits generally consist of subangular to angular shale fragments and more or less eroded and broken limy and sandy concretions. The Horse Flats deposits, which are more silty, include pond deposits. Older terrace deposits commonly are cemented, at least in part, by caliche (Johnson, 1967). Old stream channels can, in places, be traced by exposures of massive and banded travertine similar to deposits forming in present water courses (photo 3). Slack (1967) has described this process in a stream in Inyo County.

There is no necessary connection between the travertine and caliche deposits and faults or former hot springs. Except for one zone of hydrothermal alteration beneath the sole of the Santa Susana thrust at the mouth of Bee Canyon, the thrust zone is not mineralized. Where it is mineralized, the altered sediments are

Photo 1. A view north-northeast toward the bluff at the south edge of Horse Flats, west of Reseda Boulevard. The top of the bluff is the top of the Saugus Formation in this area. The average dip of the beds is 25 degrees north-northeast toward the axis of the Horse Flats syncline. Above the dashed line lie more than 61 m (200 feet) of sedimentary rocks through which there is an upward increase in abundance and thickness of beds of porcelaneous Modelo shale fragments. The thick, cliff-forming uppermost beds are caliche-cemented, coarse, angular shale fragments. (For details of cliff face at point X, see photo 2.)

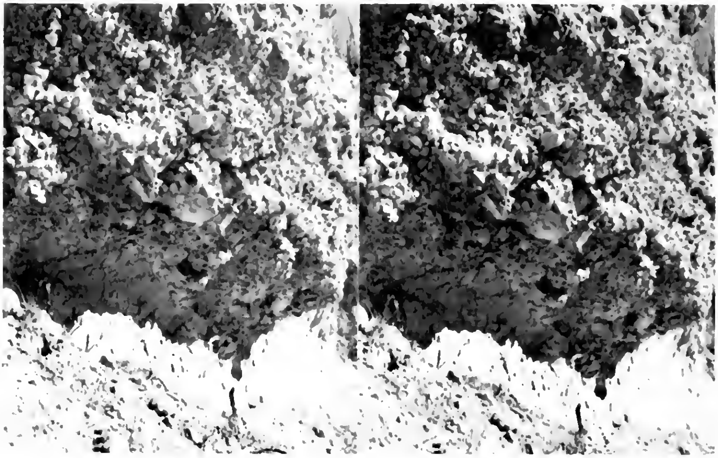


Photo 2. A stereoscopic photo showing detail of the cliff-forming unit at site X on photo 1. This unsorted, unbedded texture is typical of debris flow deposits. The bed beneath the overhang is tan-weathering siltstone, the upper surface of which is channeled.

silicified and are generally unlike caliche or travertine. Caliche and travertine deposits are, in this area, deposited by cold, calcium-carbonate-saturated ground water in or emanating from masses of carbonate-rich Modelo shale. Part of the former extent of some large, deeply eroded landslides derived from the thrust zone can be traced by resistant calcium carbonate deposits formed in them and around their former perimeters. Such deposits are part of the evidence of massive erosion of the thrust zone.

The Quaternary terrace deposits are unconformable on all older rocks. They do not appear to be deformed, but it is possible that they are cut by one or more faults within the Devonshire fault zone.

Eastern Province

Modelo Formation. In this province, the upper Miocene Modelo Formation is exposed along the axis of the Mission Hills anticline. Most of this exposure consists of platy, punky, gray-to-white-weathering diatomaceous shale interbedded with limy and concretionary layers. The diatomaceous shale is overlain by 15 m (50 feet) of brown-weathering silty shale. Along the south flank of the anticline, there is a poorly exposed, well-indurated, fine- to medium-grained, tan-weathering sandstone that may be part of the Modelo. This sequence appears to correlate with the rocks exposed above the sole of the Santa Susana thrust between Limekiln and Bull Canyons in the northern province.

Towsley Formation. Rocks of the Mio-Pliocene Towsley Formation are exposed in a sheared and faulted syncline in a fault-bounded block on the north flank of the Mission Hills anticline. Dark gray to black, brown-weathering, silty shale lies along the axis of the fold and against the northern bounding fault. Below the shale, the more exposed south flank of the syncline comprises massive, hard, light to dark brown-weathering sandstone with thin interbeds of siltstone and a few feet of hard, dark brown-weathering conglomerate at the base of the exposed section.

Pico Formation. The upper 183 m (600 feet) of the Pliocene Pico Formation were formerly (as late as the summer of 1971) exposed along the banks of Bull Creek, east of Balboa Boulevard and north of Rinaldi Street. This exposure is now largely obscured by a flood-control channel. The upper 122 m (400 feet) of this section consist of interbedded silty sandstone, sandy conglomerate, light tan and gray siltstone and gray and tan clay shale. The lower 61 m (200 feet) comprise interbedded gray to tan sandy and sparsely pebbly siltstone and silty clay shale. Except for a shell bed a foot or two thick at the contact with the overlying Sunshine Ranch Member, this part of the section appears to be unfossiliferous.

The top of the Pico Formation is exposed in bulldozer cuts and trenches just southwest of the west abutment of Lower San Fernando Dam and in cuts in the floor of the former reservoir just upstream from the dam. Here, the rocks are sparsely fossiliferous, fine, silty sandstone and sandy conglomerate grading downward into fractured claystone and clay shale. In one exposure north of the dam, highly fossiliferous, coarse-grained sandstone surrounds what appear to be disoriented blocks of silty sandstone. These blocks probably were rubble at the foot of a low sea cliff or ocean-floor fault scarp.

Sunshine Ranch Member of the Saugus Formation. In this province, the Sunshine Ranch Member is an eastward extension of the rocks exposed in the southern province except that the contact with the overlying upper part of the Saugus Formation, though distinct, is less well marked by any topographic feature. The contact is drawn in a zone of transition to the more dominantly coarse, clastic rocks at the base of the upper part of the formation and as an extension

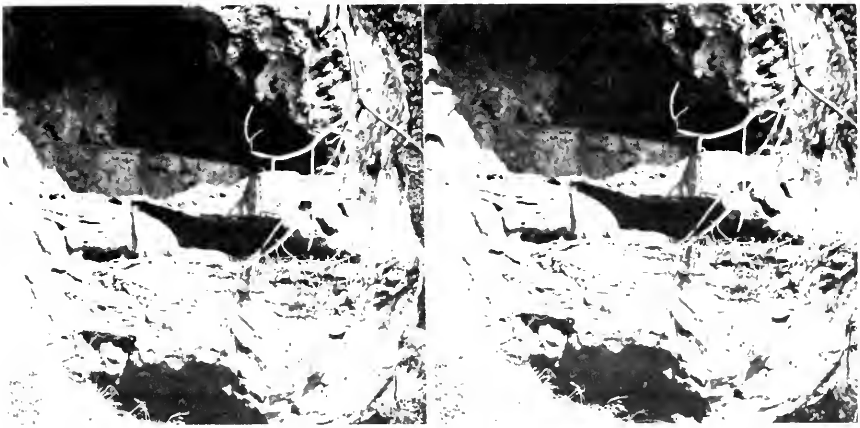


Photo 3. A stereoscopic photo of a hillslope remnant of a former water course in which rock and organic debris were cemented together with calcium carbonate derived from saturated surface water. The channel has since migrated downslope to the right. The openings are the former site of uncemented debris deposited during periods of increased flow of unsaturated water. The capping carbonate, slanting down from the upper left at the top of the picture, may be cemented debris once involved in blocking and diversion of the channel. This deposit is on the west margin of a massive landslide area lying east of the Mission Point road and about 550 m (1800 feet) northwest of the intersection of Doric Street and Neon Way.

along strike of the contact as mapped to the west in the southern province.

Upper part of the Saugus Formation. In the eastern province, the upper part of the Saugus Formation is also an eastward extension of the section exposed in the southern province, except that, on the south flank of the Mission Hills syncline, the upper beds, rich in shale fragments, are missing. The absence of the upper beds is probably due to erosion, but it may be that they were never deposited in this area. Rocks of that lithology are exposed at the west end of the syncline.

Older alluvium. In the Van Norman Reservoir-Mission Hills area, there are Quaternary alluvial deposits lying unconformably on the eroded older rocks. On the south flank of Mission Hills and south of the west abutment of the lower dam (photo 4), these beds have been tilted and faulted.

These rocks consist of interbedded, iron-stained conglomerate and sandy conglomerate derived in part from the San Gabriel Mountains and tan silty sandstone. The age of these deposits is uncertain. Oakeshott (1958, p. 86–87) considered these beds to be part of his middle to early upper Pleistocene Pacoima Formation. Weber (this Bulletin) has included them with his "older floodplain deposits." Similarly weathered, older alluvial fans of the San Dimas Formation (Eckis, 1928) lying to the east along the south margin of the San Gabriel Mountains are old enough to have been overridden by late Quaternary uplift on the Sierra Madre fault zone. West of the Van Norman Reservoir complex, deposits of similar age are most apt to resemble the uppermost beds of the Saugus Formation in being rich in Miocene shale fragments and cemented by caliche. In and west of the Aliso Canyon area, such deposits underlie remnants of an old erosion surface and, as at Lower San Fernando Dam, are unconformable on the Saugus Formation. Some of the old surface is mapped as caliche, but the original debris included such diverse material as landslide deposits (unit designated Qls in plate 2), slope wash, alluvium, and soil.

STRUCTURE

The Three Provinces

The three provinces (figure 1) are parts of structural units far larger than the areas considered in this report. The northern province is part of the Santa Susana Mountains. The southern province is the faulted and folded north edge of rocks lying beneath the San Fernando Valley. The eastern province, though it contains rocks similar in age and origin to those in the southern province, appears to have a structural history more related to the southernmost of the two blocks that comprise the west end of the San Gabriel Mountains.

The Sequence of Events and Related Features

The abrupt transition from igneous and metamorphic to sedimentary rock types in the coarse clastic beds in the upper part of the Saugus Formation marks the onset of the Quaternary orogeny in this region. The 60 to 90 m (200 to 300 feet) of conformable beds deposited during and after the transition indicate that uplift at a new source was well under way before the southern province was folded in the area where its rocks are now exposed. The abundant Modelo shale debris in the top beds of the Saugus came from the northern province. The eastern province could not have been the source. This is explained as follows.

In the eastern province, the Modelo Formation is exposed in the Mission Hills and in the foothills of the San Gabriel Mountains between Pacoima Wash

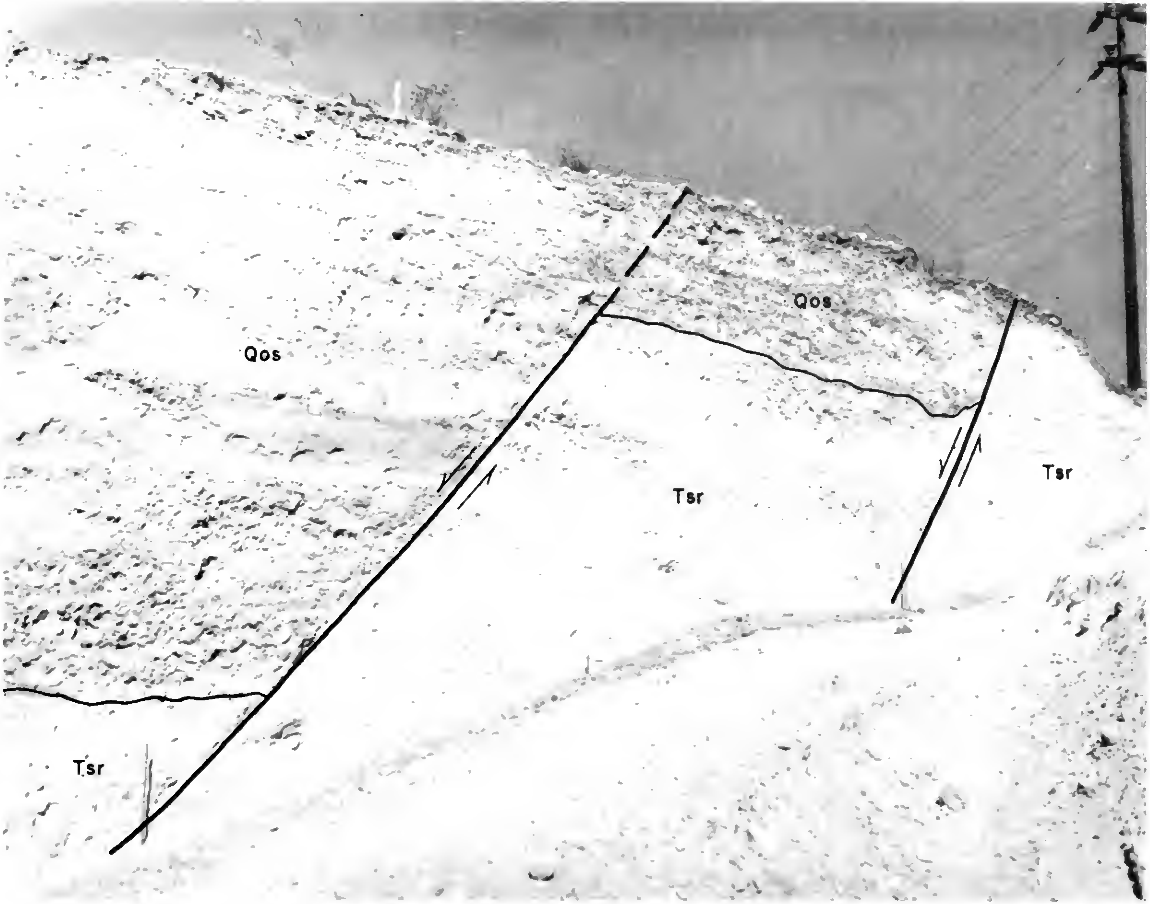


Photo 4. View northwest toward the newly cut face of an old borrow pit just south of the west abutment of Lower San Fernando Dam. Here two faults cut sand and sandy conglomerate near the base of the Sunshine Ranch Member of the Saugus Formation and unconformably overlying nearly flat-lying, older alluvium. The stake at the lower left is about 1.1 m (3.5 feet) tall. The bedding of the Sunshine Ranch Member dips 55 degrees north-northwest away from the viewer. The displacement on these faults represents inelastic response to Late Quaternary uplift of the Mission Hills anticline which lies to the east (right) of this site.

and Big Tujunga Canyon. In the Mission Hills, the Modelo Formation is not well enough exposed even now to yield the range of rock types found as clasts in the Saugus. Further, the fault system in which these hills have formed cuts the unconformity between older alluvium and the Saugus Formation. The Modelo is more completely exposed between Pacoima Wash and Big Tujunga Canyon; but, here, it was not yet deformed and uplifted when the clasts in the Saugus were deposited, for it is overlain by essentially conformable Plio-Pleistocene sedimentary rocks.

Tertiary sedimentary rocks are exposed at the extreme west end of the San Gabriel Mountains, east of San Fernando Pass; however, here the Modelo Formation is missing, either because it never was deposited that high on the surface of the older pre-Tertiary rocks or because it was eroded before the deposition of the Towsley Formation (Oakeshott, 1958, plate 1; Winterer and Durham, 1962, plate 44).

The fragments of Tertiary sedimentary rocks in the upper part of the Saugus Formation were eroded from the initial uplift of the Santa Susana Mountains.

In this area, the rocks of the southern province lie in four major folds (figure 1). From west to east they are: the Hadley anticline, the Horse Flats syncline, the Mission anticline, and the Mission Hills syncline. Except for the Mission Hills syncline (discussed later), the axial trend of these folds appears to be so divergent from the trace of the Santa Susana fault here as to suggest that they predate it; however, if the full extent of the Santa Susana fault trace is considered (Bailey, 1954), the three folds in question appear essentially parallel to its over-all trend. Furthermore, the axial planes of the Mission anticline and the Horse Flats syncline dip northeastward in accordance with the thrust-generating stress.

It seems likely that the folding of the southern province took place during the mid-Pleistocene immediately before and while it was being overridden by the Santa Susana thrust. This was the first major event in the Quaternary deformation of the region. The stress appears mainly to have been from northeast to southwest. Perhaps the more easterly orientation of the east end of the thrust zone was caused by drag in the older, less easily deformed rocks now exposed at the west end of the San Gabriel Mountains. A decrease in the magnitude of displacement at the east end of the thrust zone is suggested by the fact that the sedimentary rocks exposed there are younger than those comprising the zone of the thrust farther west. In a discussion of a 10-km (6-mile) segment of the Santa Susana thrust, Hazzard (1944) postulated a maximum north-south displacement of 2480 m (8000 feet). Ingram (1959) suggests vertical displacement of 1550 m (5000 feet) and horizontal displacement of 4 to 5 km (2 to 3 miles). If the isolated outcrop of the Modelo Formation just east of Limekiln Canyon and south of Horse Flats is the faulted remnant of a klippe, the sole of the thrust was once at least 1860 m (6000 feet) south of its present trace at Limekiln Canyon; thus the volume of rock removed by erosion during the last million and a half years would be large indeed. It is noteworthy that rocks and structures such as those described by Kahle (this Bulletin), before and beneath the Lakeview fault, are not found in this area.

In any event, the trace of the north-to-northeast-dipping Santa Susana thrust has been moved north by deep erosion. The sole of the thrust is obscured by a variety of surficial deposits, some of which cover the entire zone. I found no evidence to suggest that displacement in the fault zone has affected any of these deposits prior to the limited, local effects of the San Fernando earthquake. Indeed, the evidence suggests that the Santa Susana thrust has been inactive since the middle Pleistocene. The involvement of this fault zone in effects of the San Fernando earthquake (to be discussed later) is more aptly attributable to the fact that a small eastern segment of it overlaps the currently active west end of the San Gabriel Mountains.

Several authors (Bishop, 1950; Jennings, 1957; Slosson and Barnhart, 1967) have suggested late-Pleistocene displacement on the Santa Susana thrust. These workers described post-Saugus Pleistocene terraces as having been deformed and overridden by the thrust. Their descriptions make it apparent that they have applied the term terrace (with an attached late-Pleistocene age connotation) to the uppermost beds of the Saugus Formation. There is insufficient evidence that they were once part of a terraced landscape to define them as terrace deposits. These beds probably are no younger than middle Pleistocene, for they are (as previously described) the uppermost beds of the Saugus Formation.

Starting in the middle Pleistocene, an important group of faults developed during the folding of the Saugus Formation. Movement between the sandstone layers in the Saugus Formation forced most adjustment to take place in the weaker, clay-rich beds between the sandstone layers, as air might adjust to spaces between bent playing cards. Some of these faults were confined to a single bedding plane or to a narrow crushed zone an inch or two wide; but, just as commonly, the entire clay-rich unit was completely sheared (photo 5). Near the surface, the shear planes and voids in these faults are apt to be filled with caliche. Some faults cut across bedding (generally at low angles) between the weak beds. Such faults are most abundant in zones of intense deformation such as that near the sole of the Santa Susana fault (figure 3).

Most of the faults that parallel the folding in the Saugus Formation are a result of stress before and beneath the Santa Susana thrust. However, subsequent Late Quaternary faulting and folding in the west end of the San Gabriel Mountains has periodically reactivated many of these faults, especially those in the Mission Hills syncline as is manifest in some of the displacements that occurred during the San Fernando earthquake (photo 6).

The Aliso fault, which cuts the southwest flank of the Mission anticline, has been subject to displacement at least as late as early-to-middle Pleistocene. This fault has displaced rocks as young as the base of the upper part of the Saugus Formation. Erosion has removed any evidence of its effect on the uppermost beds of the Saugus; however, the apparent separation of the Sunshine Ranch-Saugus contact suggests small total displacement.

Photo 5. A sheared clay-rich unit exposed in a trench about 200 feet west of the west abutment of Lower San Fernando Dam. This is one of the few such beds in the basal part of the Sunshine Ranch Member of the Saugus Formation. It is one of a set of northeast-trending sheared beds and faults crossing the bed of Lower Van Norman Reservoir, and almost certainly was a site of displacement during the uplift of the Mission Hills anticline. Note the well-exposed shear plane near the head of the hammer.

The Devonshire fault zone has been active later than the Santa Susana fault. It has completely shattered the low, open arch of the Hadley anticline; and, if the Miocene rocks exposed in its zone are part of a klippe, it has cut the sole of the thrust. If the Miocene rocks are a remnant of a landslide, displacement in the Devonshire fault zone could still be considered post-thrust. One fault in this zone appears to have disturbed the old caliche-cemented surface of probable Late Quaternary age described under "Older Alluvium." The Devonshire fault probably should be considered active.

The Northridge Hills fault, a short segment of which was covered in this mapping, is a high-angle fault along which displacement has been late enough to fault and fold the uppermost beds of the Saugus Formation. Ground water flow is affected by this fault as far southeast as the San Diego Freeway (California State Water Rights Board, 1962).

The choice of the Mission Hills fault (extended as proposed in figure 1) as the west boundary of the eastern province is based upon detailed surface mapping and subsurface data. At best, this fault is only one of numerous faults that might be considered the boundary of the west end of the San Gabriel Mountains.

The greatest uplift and fault displacement in the eastern province are in and around the Mission Hills anticline (figure 2). The east-trending Mission Hills anticline has moved upward as a piercement-like structure bounded on the south by the concealed Mission Hills fault zone and on the north by a fault zone that dips north in the subsurface. The Late Quaternary age of this movement is indicated by the deformed and faulted older alluvium on the south flank of the Mission Hills and just southwest of the west abutment of Lower San Fernando Dam (photo 4). Older alluvium exposed in a trench is also faulted just southeast of the east abutment of the Upper San Fernando Dam.

During or after the upward movement of the Mission Hills anticline, the adjoining part of the province moved upward and west to southwestward. Erosion of the uplifted, north-dipping beds has produced the apparent left-lateral separation in the Sunshine Ranch-Saugus contact on the northwest boundary of the province. The actual displacement on this boundary could have been, in part, right-lateral oblique (figure 2). The right-lateral faults cutting the northeast flank of the Mission anticline could represent a northwestward dispersion of deformation on this side of the eastern province, in contrast to the south-bounding fault segment where deformation and faulting are more concentrated. At any rate, it is more logical to attribute these faults to force emanating from the eastern province than from the northern province because the probable south-southwest direction of movement of the Santa Susana thrust would have been more apt to displace such faults in a left-lateral sense near its east end.

The existence of the Mission Hills syncline is assumed on the basis of the attitude of exposed strata and a reasonable match of beds from one flank to the other. The presence and magnitude of faulting in the concealed part of this structure is uncertain. The limited subsurface data available support the presence of a southeast-dipping fault; but additional subsurface data are needed to determine the extent of this fault or of other faults, such as the Olive View, that can be projected toward the area from the northeast.

The rocks at the west end of the Mission Hills syncline (figure 3) were disturbed because they were close to the sole of the Santa Susana thrust. They were displaced to an undetermined extent by reverse faults. Whether these reverse faults continue eastward can be determined only by using subsurface information. Even if they do extend eastward, they are probably no more active than the Santa Susana fault.

The trend of the Mission Hills syncline is roughly parallel to the trace of the Santa Susana fault. Indeed, this structure probably first formed in response to stress adjacent to the east end of the fault zone; however, the present asymmetry of the Mission Hills syncline indicates greater deformation in its south flank. This deformation seems clearly to have been a response to compression on the north flank of the piercement-like block of older rocks exposed in the Mission Hills just east of Lower San Fernando Dam (figure 2).

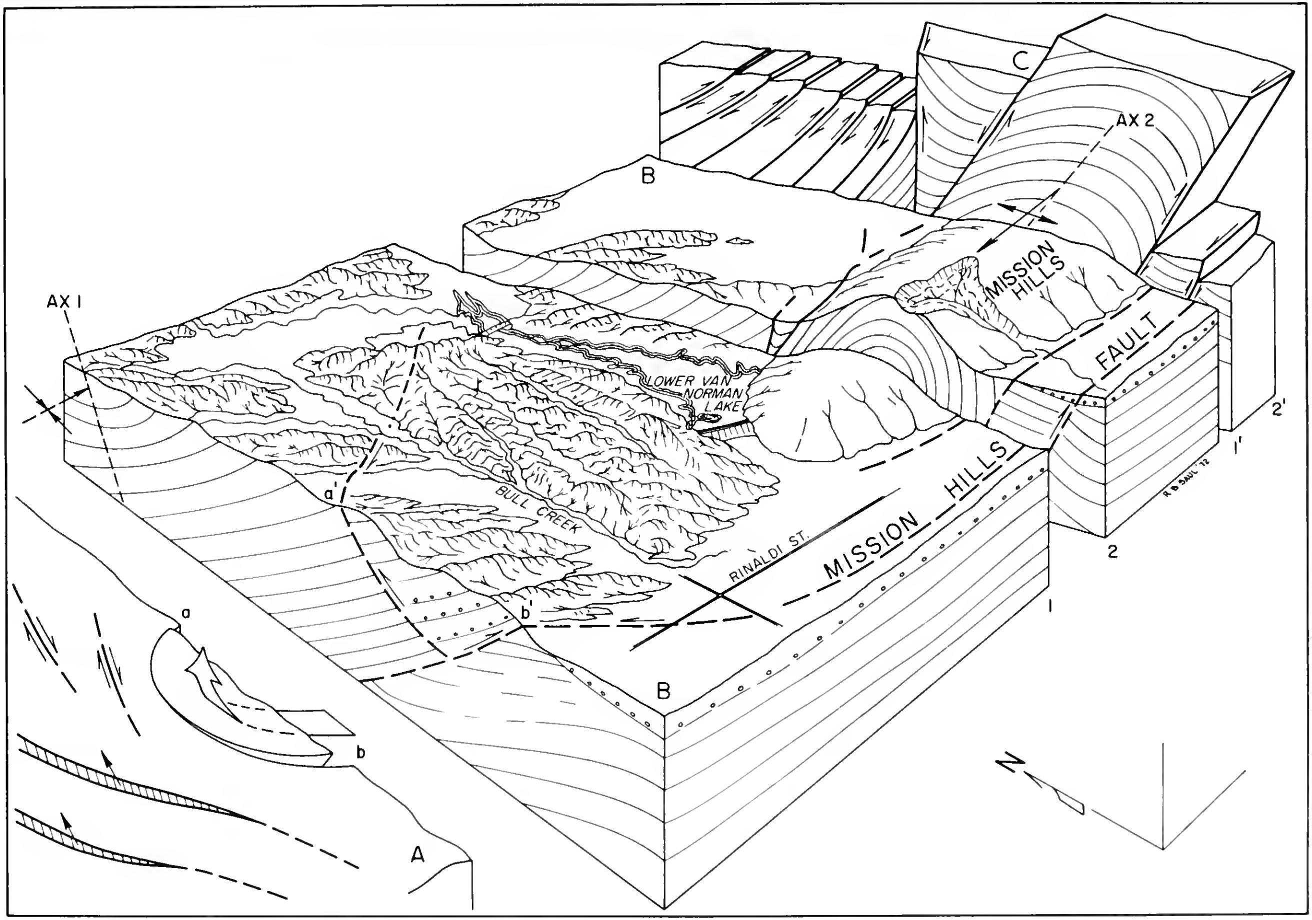


Figure 2. A generalized block diagram of the eastern province. Block A is simplified to show the possible distribution and relative direction of Late Quaternary fault displacement at the west end of the province. The eastward tilt of the west end of the province (figure 3) may be explained by the rotation of the boat-shaped block lying north of the Mission Hills fault. This is illustrated by its truncated (a — b = a′— b′) western tip in block A. Displacement at point a is right-lateral oblique. At point b, it is left-lateral oblique. Block B is a rough physiographic portrayal of the Mission Hills-Van Norman Reservoirs area including most of the south flank of the Mission Hills syncline (axial plane ax 1) and the Mission Hills anticline (axial plane ax 2). The Mission Hills are slightly exaggerated, and most urban features were deleted for emphasis and simplicity. Block C represents the section cut out of block B (1 — 2 = 1′— 2′). It is drawn as a hypothetical block diagram. The relative displacements between the various fault-bounded rock bodies is suggested. The "folded deck of cards" effect is illustrated at the north end of block C by the arrows on the west side.

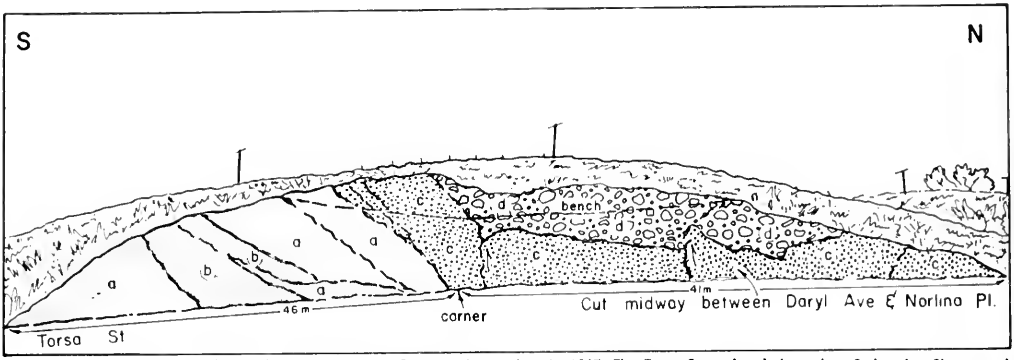


Figure 3. The west end of the graded area on Torso Street as it was late in 1967. The Torso Street break (see plate 3, location 3) occurred just south (to the left) of the Torso Street face of this cut. Units a and b are typical of the upper part of the Saugus Formation. Unit a is light-brown siltstone. Unit b is light tan sand and siltstone. Unit c is tan siltstone and soft sandstone with beds of pebble conglomerate. The pebble beds are composed predominantly of rounded, tabular, gray silty shale fragments and subordinate amounts of angular porcelaneous shale fragments. Unit d consists of crudely layered, angular Modelo shale fragments and sandstone concretions, lithologically similar and probably equivalent to the uppermost beds of the Saugus Formation (photos 1 and 2). The wavy dashed lines are planes of shearing with one-barbed arrows showing relative displacement where this is reasonably certain. The sole of the Santa Susana thrust once lay a short distance above these beds; its eroded trace now lies about 365 m (1200 feet) to the north and west of this site.

Tilt-Altered Surface Drainage

In the southern province, the drainage pattern is strongly controlled by the structure except for Limekiln Canyon, which is superposed. In the eastern province, the drainage is largely of cross-cutting, superposed character. This pattern may, in part, be attributed to the fact that the folds lie athwart the drainage issuing from San Fernando Pass; but there is also evidence of a possible Late Quaternary change in drainage pattern (figure 4). The geology of the eastern province and the effects of the San Fernando earthquake indicate upward and westward displacement of that area. Stream channel patterns suggest an eastward shift of drainage in response to eastward tilt of the part of the eastern province included in this area.

The stream course issuing from Bee Canyon, which now turns eastward, may once have flowed south through the broad channel now occupied by the insignificant north branch of Bull Creek. The three narrow valleys immediately to the east probably are normal obsequent tributaries of Bull Creek with gradients reduced by eastward tilting. The channel of Bull Creek, between its main tributary and the southern margin of the hills, and channel c (figure 4) are entrenched, possibly as a result of uplift. Data on tributaries b, c, and d were derived from pre-development (1952) vertical aerial photographs. The north fork of Bull Creek stays on the east side of its valley as does the main channel south of their confluence; and, upon leaving the hills, the main course veers sharply east like that of Bee Canyon. Bull Creek Canyon appears to have been tilted eastward. Such tilt probably was the result of Late Quaternary activation of the faults bounding the west side of the eastern province (figure 2). The San Fernando earthquake yielded data that appear to support this view, the data of greatest interest being on the direction of vertical and horizontal movement, the distribution of damaged structures (Greensfelder, 1971), and the distribution of aftershocks (U.S. Geological Survey staff, 1971).

In summary, the sequence of events in this area is:

1. Essentially uninterrupted deposition of sediments from middle Miocene to middle Pleistocene time, the uppermost beds of which record the onset of orogeny.
2. The middle Pleistocene, post-Saugus pre-older alluvium thrust faulting and folding of rocks in and adjacent to the zone of the Santa Susana thrust, and the formation of the Santa Susana Mountains.
3. Late Pleistocene to Holocene uplift of the west end of the San Gabriel Mountains and Mission Hills. Concurrent uplift and modification of the east end of the Santa Susana fault zone and adjacent associated structures. Concurrent displacement on the zones of the Devonshire and Northridge Hills faults.

Surface Breaks Associated with the San Fernando Earthquake of February 9, 1971

Surface breaks of probable tectonic origin. A surface break, clearly identifiable as a fault, disrupted the San Diego Freeway and formed low scarps and breaks in cuts and adjacent natural slopes on the north flank of the Mission Hills (57).* This displacement was reverse, north side up about 20 cm (8 inches), on bedding planes in the Sunshine Ranch Member of the Saugus Formation (photo 6). This is part of the Reservoir segment of surface breaks (Weber, this Bulletin). This displacement fits the model described in figure 2; but the mechanics of the deformation differ from the model in that the fault zone above which maximum deformation took place lies north, rather than south, of the Mission Hills. Local uplift was centered at the junction of the San Diego and Golden State Freeways. Differential vertical movement between this area and the Mission Hills exceeded 60 cm (2 feet). The break (photo 6) lies at about the 30 cm (1 foot) contour line on the south flank of the uplift (Richard R. Hopkins, Bureau of Engineering, City of Los Angeles, personal communication, 1972).

* Numbers in text key to location numbers on plate 3.

Figure 4. Late Quaternary alteration of drainage in response to uplift and eastward tilt of the area west of Van Norman Reservoirs. The stream issuing from Bee Canyon (large arrow 2) once occupied the broad, south-southeast-trending channel a (large arrow 1). Channels b, c, and d may have had their gradients lowered by tilting, thus allowing debris to accumulate in their valleys. The north fork of Bull Creek, W, occupies a valley that is broader than that occupied by the more vigorous main course. The north course, W, and the main channel south of their confluence at X, appear to have migrated to the east side of their valley (W, X, Y) and, like the present drainage from Bee Canyon, takes a sharp eastward turn as it leaves the hills (Z). Below the confluence (X), the channel (X, Y, Z) is entrenched, possibly due to uplift, and as a consequence channel c has also become entrenched.

In other exposures of the Sunshine Ranch Member and the upper part of the Saugus Formation, there were numerous small displacements on bedding planes, few of which showed measurable separations.

There was evidence of small displacements of bedding planes in a bedrock outcrop on the west shore of Upper Van Norman Reservoir. To the west, where the west end of Mission Hills syncline is exposed by grading, 1 to 2 cm (three-quarters of an inch) of reverse displacement (north side up) occurred roughly parallel to bedding. This break had a lateral extent of about 240 m (800 feet) south of and across Torsa Street (3). Where the break crossed Torsa Street, between Neon Way and Tyson Place, the sidewalks and curb were chipped and buckled by compression. For future reference, this will be called the Torsa Street break (figure 3). At this site, most of the faults probably were first caused by drag beneath the sole of the Santa Susana fault.

The westward component of movement generated by the earthquake (Greensfelder, 1971) was parallel to the axis of the Mission Hills syncline. The permanent ground deformation may have been absorbed through small parallel displacements on the many shear zones in the Sunshine Ranch Member and upper part of the Saugus Formation. Robert V. Sharp (this Bulletin) has suggested similar structural control of deformation parallel to bedding planes in folded rocks to the east of this area.

The sole of the Santa Susana thrust was the site of a small, generally left-lateral displacement traceable from a point about a half a kilometer (a quarter of a mile) northeast of the San Diego Freeway west to an area just east of the mouth of Bee Canyon (Barrows and others, 1971). The surface expression of this displacement ranges from sharp, localized offsets and cracks in bedrock and paving through parallel and en echelon zones of diffuse cracks and small rockfalls to no discernible disruption. The most obvious break was a 30 cm (12–13 inches) offset in the road to the St. Vincent de Paul Boys Camp, a bedrock exposure of the thrust (photo 7). Conversely, the alluvium of San Fernando Pass showed no clear surface breaks. To the west, this break appears to turn northwest across the zone of the thrust into the mouth of Bee Canyon where it disappears.

It is difficult to categorize this break. It probably is not tectonic in the sense that it represents fault displacement extending to great depth; however, it is at the west end of a zone of ground breaks extending eastward (parallel to and possibly coincident with an active Late Quaternary scarp) that includes a tectonic displacement just west of Pacoima Canyon (Weber, Barrows, this Bulletin). The displacement in the trace of the Santa Susana fault is most aptly described as response of a pre-existing fault to stress originating in another fault system.

Structural damage relatable to this break includes minor damage to the Metropolitan Water District Balboa Inlet Tunnel about 490 m (1600 feet) from the south portal (Duke, 1971, p. 234). The reinforced-concrete bridge, built where Balboa Boulevard crosses the freeway, was jammed against its southwest abutment (18). The projected trace of the sole of the thrust passes beneath this structure. The northwest leg of a steel power-line tower, situated in the zone of the thrust, buckled, suggesting up-dip displacement (photo 8). At this site, overlooking the west side of San Fernando Pass, displacement appears to have been less confined to the sole of the thrust.

The Cascade oil field lies about a half a kilometer (a quarter of a mile) north of the surface breaks on the Santa Susana thrust. Wells in this field penetrate

Photo 6. A stereoscopic photo of the break on bedding planes in the Sunshine Ranch Member of the Saugus Formation in a freeway cut just east of Lower Van Norman Reservoir (57).

the sole of the thrust. The wells in the Aliso Canyon oil field also penetrate the thrust but in an area less disturbed by the San Fernando earthquake. The following observations were made by and obtained from California Division of Oil and Gas engineers R. Johnson and G. Ledingham on February 18 and 19, 1971:

> "McCulloch well No. 'Mission-Visco' [Cascade oil field] 1 sanded up and was being pulled; well No. 'Mission-Visco' 2 was shut down due to a landslide; and well No. 'Mission-Visco' 3 was shut down due to movement of the pumping unit in response to settling of the mat fill. Several oil field pipelines were broken, and many road surfaces were cracked. It was reported that the field seemed to be producing more gas after the earthquake."
>
> "Getty Oil Company well No. 'SFZU' F-2 [Aliso Canyon field] was covered by a landslide and the road leading to the well was closed. Getty Oil Company wash tank at No. 2 gathering site Standard Oil Company 'Sesnon' wash tank and Standard Oil Company 'Frew' wash tanks had been damaged and were not operating. Standard Oil Company 'Del Aliso' wash tank has been damaged but appeared to be in use. Many oil field pipelines were broken. Several landslides were observed, and at least three roads were closed."

Two breaks formed across the north-northwest-trending crest of the cliff on the northeast wall of Bee Canyon (9) northwest of Cascade oil field. The smaller, more northerly break was down 15 cm (6 inches) on the south side; and, near by, the more southerly break was down about 60 cm (2 feet) on the south side. Where exposed in the scar of a fresh rockfall, the southern break appears to have resulted from renewed movement on pre-existing shear planes, whose iron-stained surfaces dip 75° north at the top of the cliff and appear to curve to a shallower angle, roughly coincident with the bedding about 60 to 90 m (200 to 300 feet) across the cliff face. The subsurface configuration of the north break is not evident.

Other surface breaks. Just north of Lower San Fernando Dam, a bedding-plane fault is exposed on the crest of an isolated prominence, the upper 6 to 10 m (about 20 to 30 feet) of which stood above water as an island in the former reservoir. A displacement of 2 cm (about three quarters of an inch), down on the north side, occurred at the top of the island (53). This fault was subsequently traceable some 250 m (about 820 feet) southwest through two artificial cuts, but there was no discernible displacement in those exposures. The significance of this break is not certain. Such a small displacement demands optimum surface conditions for expression; a bedrock surface normal to the direction of movement like that at the top of the island, for example. Most of the west slope of the island is covered by loose cobbly sand. Cracking followed down the bedding across the narrow exposure above the water line on the steep east slope of the island. If this break had great lateral extent, most of it would have been under wet unconsolidated sediments and water. During the draining of the reservoir, wave action and aftershocks would have further reduced surface expression. The strongest arguments against calling this break tectonic appear to lie in the possibility of its being ridge-top lurching and in that it does not fit the model proposed in figure 2.

A bedding plane displacement in the shale of the Modelo Formation was found near the water line just east of the lower dam. This break was not found in pristine condition, and the degree of modification by water or shaking was not evident. It has an exposed length of 4 to 5 m (about 15 feet) and is up on the

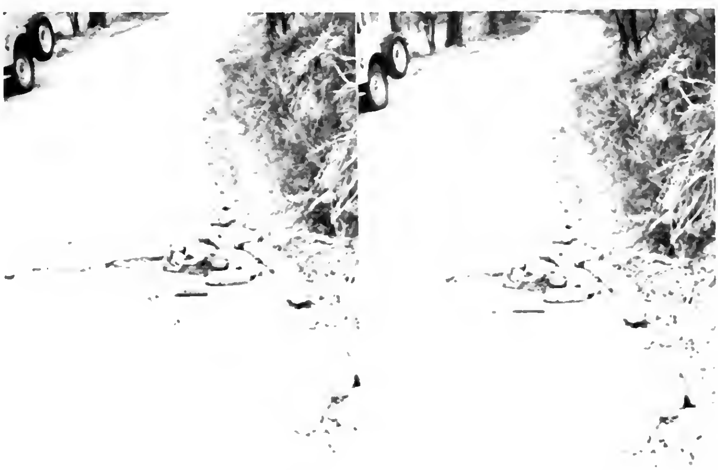


Photo 7. A stereoscopic photo looking north toward the break where the road to St. Vincent de Paul Camp road crosses the sole of the Santa Susana fault (7). The left-lateral displacement is slightly greater than 30 cm (a foot).

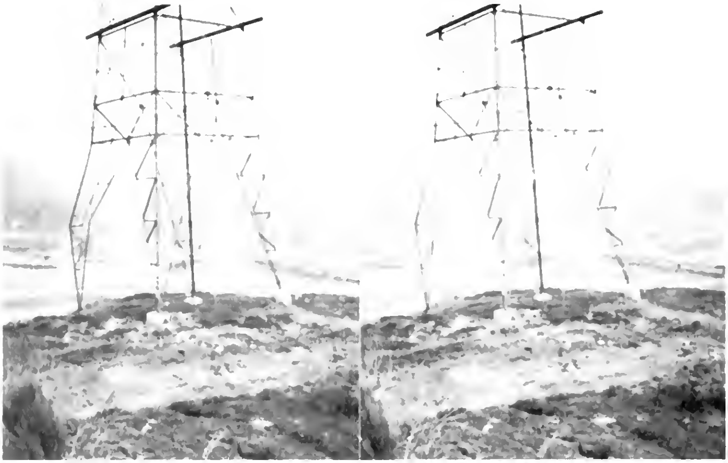


Photo 8. A stereoscopic photo showing a view northeast along the zone of the Santa Susana thrust. The damaged northwest leg of the tower suggests a force from the northwest with a possible upward component. San Fernando Pass and the Balboa Boulevard overpass are in the background.

Photo 9. A stereoscopic photo of the shattered-ridge effect on a ridge east of the mouth of Bee Canyon. Cascade oil field is in the background. Note light-colored remnants of the pre-earthquake surface.

northwest about 10 cm (4 inches). The northeast end of this break appears to be truncated by a joint or fault of small displacement. Similar joints or faults are common in exposures up the slope, and it is possible that this isolated break resulted from downslope rotation of a block of shale either during the earthquake or at some earlier time. In the latter instance, lakeshore erosion could have considerably modified the evidence. A tectonic origin for this break cannot be completely discounted without more data on the detailed geology of this slope.

One manifestation of locally intense ground motion was the "shattered ridge" (photo 9). West of San Fernando Pass, this effect was concentrated, with few exceptions, in and near the Santa Susana thrust zone on a group of low ridges northeast of the mouth of Bee Canyon.

On a typical "shattered" ridge, the accumulated weathered rock and soil appears to have been tossed (photo 9). The suggested vertical acceleration greater than 1 g is difficult to account for in the area in which the ridges lie, but it is possible that local refraction of wave motion took place. (See Davis and West, this Bulletin). Effects of strong motion are in a zone in and south of the Santa Susana thrust. In the Bee Canyon area, part of the thrust zone was affected. To the west, the effects are concentrated in a rapidly narrowing belt south of (beneath) the sole of the thrust. The sole of the thrust marks a sharp lithologic and topographic break. As Richter (1958, p. 60) stated, "Normally we expect earthquake intensity to be higher on loose material than on basement rock; but this holds only when there is no great difference in conditions along the path. Then the absorption of energy takes place chiefly near the surface, but the amplitude of seismic waves is actually increased there and the effects on structures are greater."

Some ridges bear evidence of both horizontal and vertical movement. One such ridge is a hogback just above the zone of the Santa Susana thrust and west of the Cascade oil field (8). The crest of this narrow steep-sided prominence had been graded for a drilling site (photo 10). Bedding planes in both the natural and cut surface parallel the crest of this northeast-trending ridge and dip 60° to 75° southeast. Vertical displacement in excess of 30 cm (1 foot) occurred on one bedding plane, and numerous lesser displacements and tension cracks opened up along other planes. Locally, the tension cracks give the ridge the appearance of opening like a book standing on its spine. Abundant rockfalls scar the flanks of the ridge.

A break occurred on a ridge in the zone of the thrust north of the Torsa Street area (5). Here displacement between shale and overlying sandstone caused a crack about 25 cm (10 inches) wide and 25 cm (10 inches) down on the the south side. The trend of this ridge is normal to the bedding. The cracking diminished down the flanks of the ridge, becoming untraceable before reaching the bottom.

On some ridges near the mouth of Bee Canyon, slumps occurred on the northeast-facing slopes in greater abundance than on those facing southwest. This could be viewed as inertial lag behind a northeast-to-southwest force, but other factors complicate this simple view. Northeast-facing slopes tend to be more moist, better wooded, and more deeply mantled with surficial deposits than those with southwest exposure. Horizontal motion is suggested on some disturbed ridge tops (photo 9) by preferred orientation of soil clods bearing remnants of the pre-earthquake surface, but these effects commonly grade downward into slope failures, and more often than not such orientation can be related to some such feature.

Most slope failures were earthquake-triggered slumps or rockfalls at sites where such features have been a major part of the normal mass-wasting process and could have been expected. Renewed movement occurred in some old landslides, one of the most important being in the face of the Balboa Boulevard cut southwest of the freeway overpass (17). Here excavation removed support from the head and crown of an old slide. Earthquake shaking triggered movement in the poorly supported mass. Highway cuts experienced similar failures at San Fernando Pass (Evans, this Bulletin).

Some cracks in streets and structures in subdivisions in the hilly area west of the Van Norman Reservoir complex may be attributable to displacement between fills and subjacent materials, but such boundaries are not generally easy to trace. A crack on the east side of Darla Avenue (4) may be considered an example.

Whatever their cause, the shattered ridges and adjacent slope failures here and in other areas affected by the San Fernando earthquake present problems for consideration in future development. Even such older,

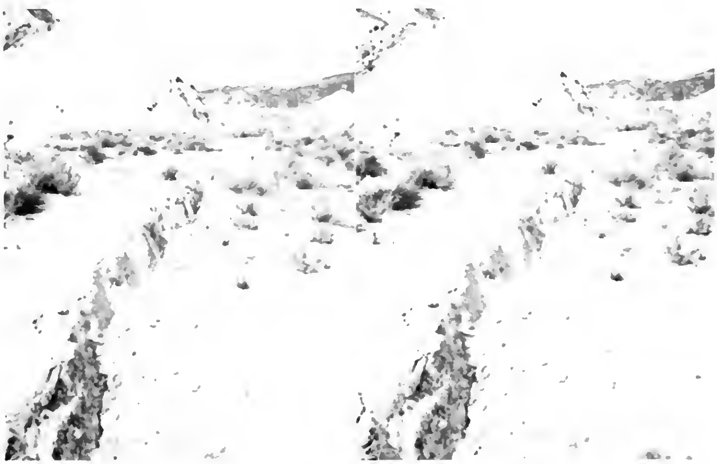


Photo 10. A stereoscopic photo of a break in an artificial surface cut on a ridge just above the Santa Susana thrust and just west of Cascade oil field (8). Note the steep dip of the bedding in the cut in the background. The scarp is about 30 cm (a foot) high. The viewer is looking northeast.

probably inactive fault zones as the Santa Susana should be suspect as potential zones of refraction and related surface effects.

Most of the cracking affecting low-lying alluvial surfaces west of the San Diego Freeway was concentrated in and around Upper Van Norman Reservoir. Here, Quaternary sediments lie in the eroded axial trough of the Mission Hills syncline. Both surface water and ground water is normally ponded in this area.

The Torsa Street break (3) may be a manifestation of westward compression in the area northwest of the Van Norman Reservoirs. The same sense of motion is seen in the response of surface structures too rigid to absorb all of the force by compression. East-west-oriented blacktop facing on levees around Upper Van Norman Reservoir moved westward, buckling and overlapping pavement on the west side. Upper San Fernando Dam bowed about 1.5 m (5 feet) downstream. In the Van Gogh School area, curbs and sidewalks were chipped and buckled. The period of shaking following the initial shock resulted in a general subsidence and eastward and southeastward movement of alluvium. This caused numerous tension cracks in the alluvium and in such slightly compressed bodies as the recently laid blacktop pavements in the area around Van Gogh School (6). The pattern of tension cracks suggests that the direction of subsidence may have been controlled, to some extent, by the configuration of the bedrock. This and similar cracking to the east is attributed to landsliding by Youd and Olsen (1971).

Abundant large slumps damaged levees at the north end of Upper Van Norman Reservoir, and one slump heading just north of the powerhouse disconnected that structure from the aqueduct tube. Sand boils in the lake bed adjoining some levee failures indicate at least partial liquefaction of unconsolidated sediments during earthquake-induced shaking.

March 31 Aftershock

The impact of the damaging March 31 aftershock was most severe in the vicinity of Rinaldi Street and Wilbur Avenue (2) in Granada Hills. The epicenter of this event was beneath the Mission anticline at a depth of 2 km (a mile and a quarter), about 2.4 km (a mile and a half) to the northeast of the above intersection (Allen, personal communication, 1972). The magnitude was 4.6 as reported by the California Institute of Technology. Ground cracks opened in older alluvium south of Rinaldi Street in the vicinity of Yolanda Avenue, where two houses were severely damaged; cracks opened between bedrock and fill north of Rinaldi Street along Yolanda Avenue. Several two-story, single-family dwellings on Twin Hills Avenue, about 1.6 km (a mile) northwest of the Rinaldi Street-Wilbur Avenue corner, required extensive repairs to dry-wall interior finish and brick chimneys. In addition, some cracks that opened during the February 9 earthquake were reactivated during this aftershock. Surface effects of the aftershock appear to lie along the general trend of the Devonshire fault zone as projected southeast beneath alluvium.

At the Darby Street Elementary School (1), about 1.6 km (a mile) southeast of the Rinaldi Street-Wilbur Avenue intersection, the blacktop in the school yard was compressed. The principal manifestation of the compression consisted of arcuate folds, convex toward the east and southeast, as much as 10 cm (4 inches) high and about 1.5 m (5 feet) from crest to crest. These wave-like folds formed in two groups. The larger group—three well-developed folds and one low indistinct fold with a lateral extent of about 15 m (50 feet)—formed about 39 m (130 feet) northwest of the southeast corner of the school yard. The second group—two lower, less distinct folds of slightly less lateral extent—lay on a line with the larger group and about 30 m (100 feet) north of it. The school buildings sustained only minor damage.

CONCLUSIONS

Except for limited, coincidental response to the February 9 earthquake at its east end, the Santa Susana fault probably has been inactive since the middle Pleistocene. The faults most active during the earthquake cannot be equated to the Santa Susana fault in time or space; however, the Santa Susana fault zone appears to have caused increased ground motion in and near the area of its outcrop by serving as a surface of reflection and refraction of seismic waves.

Late Quaternary uplift of the west end of the San Gabriel Mountains appears to extend, or at least to have affected, rocks, structures, and stream courses as much as 2.4 to 3.2 km (a mile and a half to 2 miles) west of the Van Norman Reservoirs. The San Fernando earthquake is the latest event in this uplift.

The Devonshire and Northridge Hills faults, lying en echelon and west of the February 9 break, have been sites of Late Quaternary displacement and probably are active.

Evidence from detailed geologic mapping suggests that the Sunshine Ranch "Member" should soon be elevated to the rank of *formation* and that at least one new member should be recognized at the top of the Saugus Formation.

CHAPTER 6

Surface Effects and Related Geology of the San Fernando Earthquake in the Sylmar Area

by F. Harold Weber, Jr.[1]

ABSTRACT

Most of the economic loss from the earthquake occurred in the Sylmar area. This loss was due partly to the surface effects of faulting, partly to ground shaking, and partly to a combination of faulting and shaking. The principal surface effects of faulting occurred on the San Fernando fault zone, along the south edge of the Sylmar inlier of the San Fernando Valley.

Minor surface effects of the earthquake occurred along the Santa Susana fault zone southwest and northeast of San Fernando Pass. There was small left-lateral and reverse displacement along the lower Santa Susana fault northeast of the pass for at least 450 m (1500 feet). Here the Sunshine Ranch Member of the Saugus Formation of Plio-Pleistocene age was faulted south over the upper member of that formation. Shattered ridges to the north of the fault suggest that intense ground shaking occurred in the area.

Detailed mapping east of Grapevine Canyon disclosed a series of thrust faults which apparently place succeedingly older rock units over younger ones, from Pacoima Formation of middle Pleistocene age at the base to basement complex of pre-Tertiary age at the top. There were minor surface breaks along tension(?) faults north of the eastern lower Santa Susana fault which extends concealed along the front of the San Gabriel Mountains from Sombrero Canyon to the Olive View Hospital area. Pre-earthquake reverse displacement along this fault of the surface on which the marine Towsley Formation (late Miocene-early Pliocene) was deposited may be greater than 3.5 km (2 miles). Northwest of the Olive View Hospital complex, there were minor surface effects along the eastern lower Santa Susana fault and possibly along the Olive View fault. These faults respectively place undifferentiated Towsley/Pico Formations over Pacoima Formation and Pacoima Formation over older alluvium of late(?) Pleistocene age. The Olive View Hospital complex probably was damaged principally by ground shaking. An east-northeast-trending fault may extend concealed beneath alluvium along the front of the foothills there. If activity occurred along the fault at depth, perhaps shaking was amplified at the surface in the vicinity of the hospital.

Ground cracks and sand boils developed in the northwestern Sylmar area, accompanied by severe damage to the San Fernando Juvenile Hall, Golden State Freeway, Pacific Intertie Terminal, and other facilities. Strong curvilinear cracks in alluvium northeast of the Juvenile Hall extend southwest. Their development accompanied settling, lurching, and possible sliding along wet, fine sandy layers which liquefied during shaking. Similar ground cracks were also common for 0.8 km (half a mile) north and northeast of the Juvenile Hall, and were well developed 1.6 km (1 mile) to the west. Branch faults of the Santa Susana zone may project northeast through the Juvenile Hall area, and activity along these faults beneath the surface of alluvium may have amplified shaking in the area.

The San Fernando fault zone extends east-northeast into the Mission Hills through the site of Lower San Fernando Dam, part of which failed by sliding north into Van Norman Reservoir (see Cortright, this Bulletin). No fault rupture is known to extend into the dam. The Reservoir segment of the fault zone is the name used in this report for the complex of faults northeast of the dam site. The principal fault break of the segment was wholly in artificial cuts in the Sunshine Ranch Member of the Saugus Formation. It trends east, dips north, and is 300 m (1000 feet) long; it shows left-lateral and reverse offsets.

The Mission Wells and Sylmar segments of the San Fernando fault zone trend east-northeast in alluvium through heavily populated portions of Sylmar. Spectacular ground rupture and accompanying fault breaks formed a swath perhaps 360 m (1200 feet) wide and demonstrated large left-lateral, normal (vertical), and shortening (thrust) components of fault movement. The faults dip about 50°–60°N., essentially parallel to bedding of the succession of Modelo Formation, Towsley/Pico Formations, and Saugus Formation, which lie mostly beneath a veneer of alluvium.

Pre-earthquake scarps along the Sylmar and Mission Wells segments are delineated topographically on the old San Fernando topographic quadrangle maps of the U. S. Geological Survey. A fault north of the Sylmar segment, with a scarp also delineated topographically, is exposed in the Foothill Freeway. Although only slightly active during the earthquake, it shows older alluvium on the north faulted up perhaps 30 m (100 feet) or more. Apparently none of these faults was mapped before the earthquake.

The earthquake caused damage away from areas of obvious fault rupture in the gently sloping Sylmar area. The damage is assumed to have been caused by ground shaking. Some street cracks may be parallel to bedding-plane faults in the Saugus Formation which is assumed to underlie the alluvium.

Study of the surface geologic effects of the earthquake and of the areal geology in the Sylmar area shows a complex relationship between faulting, ground shaking, and damage. Better understanding of the geologic environment and its probable response to future earthquakes is necessary for wise future land-use and building design.

[1] California Division of Mines and Geology, Los Angeles.

As used here, the Sylmar area includes most of the community of Sylmar in the city of Los Angeles along with the city of San Fernando and adjoining portions of Los Angeles County in the San Gabriel Mountains and foothills. Most of the structures damaged in the earthquake were in this area, as follows: water storage and electrical transmission and conversion facilities of the Los Angeles City Department of Water and Power; facilities under construction for Metropolitan Water District of Southern California; Los Angeles County Olive View Hospital; dams and other facilities of the Los Angeles County Flood Control District; Golden State, Foothill, and San Diego Freeways; San Fernando and Sylmar Industrial Parks; Holy Cross Hospital; Indian Hills Medical Center; and a large number of commercial and apartment buildings, schools, single-family dwellings, underground utility lines, and streets.

The damage occurred almost wholly within about 15 seconds of the initial shock at 6:01 a.m. on February 9, 1971. The resultant geologic effects ranged from slight to spectacular, with the range of damage at each construction site or locality being dependent upon its particular relationship to these geologic effects. It is the purpose of this report to describe the geologic effects and to relate them generally to the damage. In contrast, there have been numerous studies made of individual sites where damage occurred, and many reports have been written covering specialized topics of the geology and seismology of the earthquake (consolidated references, this Bulletin).

This report is based on nearly a year's study in the field of the geology related to the earthquake. The work began as a reconnaissance of the entire region in collaboration with colleagues of the California Division of Mines and Geology and phased into a detailed study of the Sylmar area, using maps of the scale of 1 inch equals 400 feet provided by the City of Los Angeles. In addition, post- and pre-earthquake aerial photographs and the U.S. Geological Survey San Fernando topographic quadrangle (1966) were used in mapping.

This report supersedes previous reports (Barrows and others, 1971, and California Division of Mines and Geology, 1971) on surface effects of the 1971 earthquake in the Sylmar area prepared by the California Division of Mines and Geology.

GEOLOGIC SETTING OF THE SYLMAR AREA

The Sylmar area includes the very western part of the San Gabriel Mountains, which are separated from the Santa Susana Mountains to the west by San Fernando Pass. The Santa Susana fault zone bends northeastward from the frontal area of the Santa Susana Mountains into the steep front of the San Gabriel Mountains, but faults of this zone broke at the surface only minimally during the earthquake.

South of the San Gabriel Mountains lies a gently south-sloping surface or plain which is an inlier of the northern part of the San Fernando Valley. This surface is separated by the Mission and Pacoima Hills from the major part of the valley to the south. Most of the damage from the earthquake occurred within the Sylmar inlier or along its edges, because of the proximity of the epicenter to the concentration of people and construction there.

At the south edge of this inlier lies the western part of the San Fernando fault zone, the principal zone of faulting involved in the earthquake. This zone was not recognized in the Sylmar area before the earthquake, although portions of it had been mapped, especially in the Lower Van Norman Reservoir area by Kew (1924), Union Oil Company (1953), Bailey and Jahns (1954), Jennings (1957), and Oakeshott (1958). In addition, an impediment to the southward flow of ground water out of the Sylmar area, as described by California State Water Rights Board (1962), is essentially along faults of the San Fernando zone (Brown, this Bulletin). Faults of the zone may extend southwestward from the Sylmar area at least as far as Chatsworth in the very western part of the San Fernando Valley; to the east, they extend to Sunland, where they join the Sierra Madre fault zone. Three segments of surface breaks were named during studies immediately after the earthquake by geologists of California Institute of Technology (Kamb and others, 1971) and the U. S. Geological Survey Staff (1971). These are the Mission Wells, Sylmar, and Tujunga segments. One additional segment, the Lakeview, was defined by the California Division of Mines and Geology (Barrows and others, 1971, and this Bulletin). A fifth segment, the Reservoir,is delineated in this report.

In the following pages,the geologic effects of the earthquake in the Sylmar area are described generally in order from west to east, beginning with the Santa Susana fault zone in the San Fernando Pass area and extending east and southeast to the eastern end of the Sylmar segment of the San Fernando fault zone near the Pacoima Wash.

GEOLOGY AND SURFACE EFFECTS IN THE SYLMAR AREA

Santa Susana Fault Zone

The Santa Susana fault zone extends northeastward from the Santa Susana Mountains across San Fernando Pass and into the San Gabriel Mountains. Faults of the zone extend eastward along the front of the mountains to the vicinity of Olive View Hospital. Such faults as the Sombrero seem to split from the zone and trend toward the north-northeast into the range. Also included in the zone are probable concealed faults that extend northeastward across the Van Norman Reservoir area to the vicinity of Olive View, where the Olive View fault is exposed. The area of these concealed faults is described in a later section of this report.

San Fernando Pass area. The Santa Susana fault zone in the San Fernando Pass area consists of two principal faults, which are referred to as the lower and the upper Santa Susana faults (photo 1). The trace of the lower fault, both southwest and northeast of the pass, was clearly expressed by the effects of the earthquake. A mole track and accompanying features due to shaking extend northeastward into the Sylmar area from the Oat Mountain quadrangle (Saul, this Bulletin). From a point about half a mile (1 km) south-southwest of the pass, a mole track was traced north-

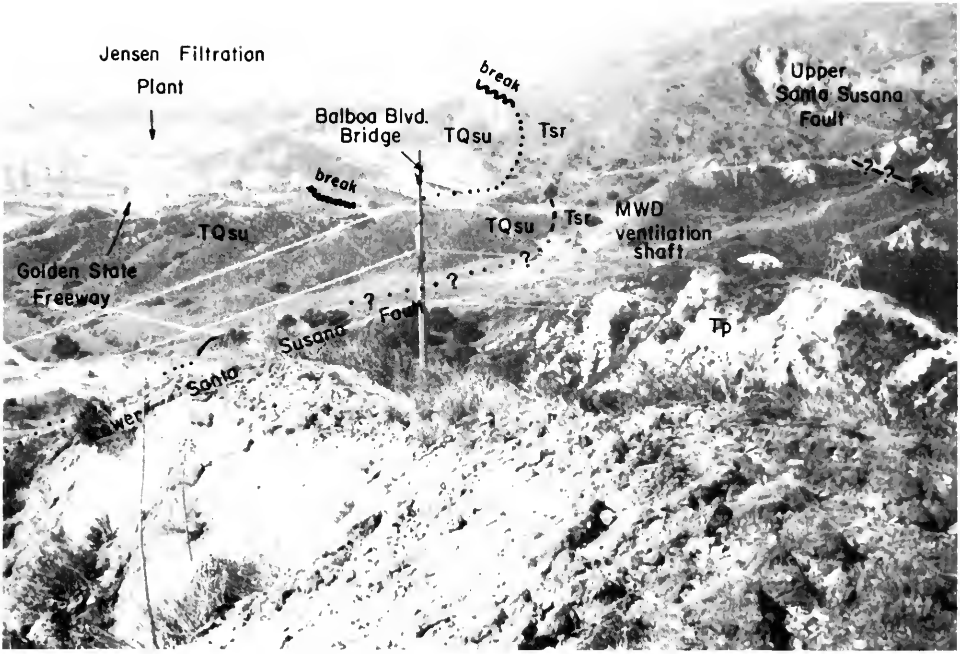


Photo 1. View southwest from north of Grapevine fault down south slope of San Gabriel Mountains over ridge top underlain by terrace deposits (Pacaima Formation?). The thin veneer of soil on ridge crest shattered during earthquake shaking and slid down the steep slope. Light-colored ridges to right are resistant sandstone and conglomerate of the Pico Formation (Tp). In background, northeasterly breaks along Santa Susana fault zone are visible; along lower fault, Sunshine Ranch Member of Plio-Pleistocene Saugus Formation (Tsr) is thrust southeast over younger upper member (TQsu).

northeastward across a swale and up onto a flat area roughly 180 m (600 feet) west of Balboa Boulevard and just west of the top of the large road cut there (12). The fault break extended down the north side of this hill but could not be traced northward into a pre-earthquake bedrock landslide. No break was found north of the landslide in colluvium above the fault in a small canyon or beyond in fill for the Golden State Freeway (plate 2); but it is in this area, beneath the colluvium in the canyon and apparently in the plane of the fault, that the Balboa feeder tunnel of the Metropolitan Water District was severely cracked during the earthquake (19). This location was given by H. J. Mills, general manager of the District, as about 1500 feet north of the south portal (Duke, 1971, p. 226). Cracks also appeared approximately along the trace of the fault in part of the freeway and in the eastern aqueduct tunnel of the Los Angeles City Department of Water and Power beneath the freeway. The Balboa Boulevard bridge, which crosses the freeway above the concealed fault, was severely damaged (18).

Northeast of the freeway, a mole track was traced in bedrock at least 450 m (1500 feet). At one locality (20) along this trace, steeply dipping to overturned beds of the Sunshine Ranch Member of the Saugus Formation clearly overlie younger, generally very gently southeast-dipping beds of the upper member of the Saugus Formation (photo 2). Here the caliche-bearing fault trace extends along a steep outcrop and displays left-oblique offset of 8 to 10 cm (3 to 4 inches), although this figure may be exaggerated slightly by landsliding. The dip of the lower Santa Susana fault is about 20° N. In this area, Winterer and Durham (1962, plate 44) mapped the fault 150 m (500 feet) north of its actual location and show the actual location as a depositional contact between the Sunshine Ranch Member and the upper member of the Saugus Formation. Intense shaking in the area is suggested by shattered earth on ridges, such as that located about 230 m (750 feet) north of (20) (photo 3).

Intensified shaking or slight displacement may have occurred along the upper Santa Susana fault between the Golden State Freeway and Grapevine Canyon, where prominent cracks extend across several ridges (23). To the west, activity along this fault may have caused damage to the aqueduct lines just north of the cascades (21). Another ground crack in this area seems to show small left-lateral offset along a branch of the Santa Susana fault zone (22).

The U. S. Geological Survey Staff (1971, p. 75) reported that no tectonic movement occurred along the Santa Susana fault, and geologists of the California Institute of Technology (Kamb and others, 1971, p.

Photo 2. Displacement of lower Santa Susana fault during earthquake was about 8–10 cm (3–4 inches) of left-oblique slip where well exposed beneath yucca plant in middle ground. Much of the bare area shown on the right was caused by rockfalls during shaking. View northeast is about 75 m (250 feet) northeast of Foothill Boulevard in San Fernando Pass (locality 20). Fault is well defined by a very thin white layer of caliche, with nearly vertical beds of lower, Sunshine Ranch Member of Saugus Formation thrust over gently southeast-dipping upper member of Saugus Formation of Plio-Pleistocene age. Fault break was represented by mole track in grass-covered ground to left of point where photograph was taken. *Photo by James E. Kahle.*

41–54) did not discuss the fault zone. Nevertheless, Meehan (1971, p. 241) noted that movement occurred on the fault. The surface breaks of the Santa Susana fault zone in the San Fernando Pass area extended generally along a part of the western edge of the Chatsworth segment of the aftershock area, as shown by Hanks and others (1971, p. 21–23, figure 1). Perhaps several of these aftershocks, reported to have occurred at depths of 9–11 km ($5\frac{1}{2}$–7 miles), may have occurred down dip from the surface breaks of the fault zone.

Grapevine Canyon-Sombrero Canyon area. In the northeast fork of Grapevine Canyon, cracks occurred in alluvium and fill, and one slight break may have occurred along a fault of the zone just north of a ranch house which was severely damaged and later razed (24). In addition, breaks occurred in a major gas line that extends through the area, but the ground along the traces of faults was not examined thoroughly soon enough after the earthquake to determine whether ground cracks here were directly related to faulting. One mole track in the area extended north-northwest down a hill slope for 50 m (160 feet), entirely within the upper member of the Saugus Formation, where shattered ridges and landslides are common; but it does not seem to be part of a through-going fault (25).

The Grapevine fault (Oakeshott, 1958) is a reverse fault which separates basement complex from the Towsley and Pico Formations. This and additional faults in the area also have been mapped by Holloway (1940), Merifield (1958), and Winterer and Durham (1962). The Grapevine fault was examined for signs of activity after the earthquake, but none was discovered (plate 2). Possible minor, pre-earthquake faulting occurred in the very southwest part of Pleistocene terrace deposits (Pacoima Formation?) north of the east fork of Grapevine Canyon; but the Grapevine fault does not seem to offset these deposits.

The Santa Susana fault zone continues east from the upper part of the northeast fork of Grapevine Canyon to the Olive View Hospital area. Features associated with shaking and possible small displacements occurred during the earthquake along faults of this zone in partial reflection of the very complicated, pre-existing fault pattern. Faults are very difficult to map in this area because of this complexity, and because the lithology of late Miocene to middle Pleistocene clastic sedimentary rocks (the Towsley, Pico, Saugus, and Pacoima Formations) commonly changes so gradually and subtly that division and recognition of mappable units is very difficult. Furthermore, many outcrops are severely weathered and thus difficult to study, and older alluvium conceals many parts of faults.

In the Oat Mountain area to the west, oil well data from the Aliso Canyon field indicate that the lower Santa Susana fault has an apparent fold in it (Holston, 1952). Similar folding or bending-over may have occurred along the fault zone here, further complicating the structural picture.

The present mapping demonstrates that, in the area between the east fork of Grapevine Canyon and the vicinity of Sombrero Canyon, development of a series of thrust faults has placed older rock units

Photo 3. Where shaking was intense during earthquake, soil mantle along crests of ridges shattered or popped apart and gravitated down slope. Scene shown here is about 230 m (750 feet) northwest of break along Santa Susana fault (out of picture to left); the fault trends southwest beneath fill for Golden State Freeway in San Fernando Pass in left distance and extends southwest up canyon shown at center of top of photograph. *Photo by Allan G. Barrows.*

successively over younger units (plate 2). At the base of the series, fractured and sheared Sunshine Ranch Member of the Saugus Formation is partially thrust over Pacoima Formation or older alluvium; next, undifferentiated Towsley/Pico Formations are thrust over the Sunshine Ranch Member; and at the top of the sequence lies gneiss of the basement complex which is brecciated along the fault contact but retains its lithologic character at the top, giving the appearance of a possible gravity fault of tectonic origin, rather than that of a landslide. The lowermost and most southerly fault, as partly projected from Grapevine Canyon to the Olive View area, is termed the eastern lower Santa Susana fault (plate 2). No evidence was discovered for the south-trending San Fernando fault as mapped by Merifield (1958).

Geologic surface effects of the earthquake in this area were limited mostly to landsliding. One group of small breaks, up on the south side, extends across a ridge north-northeast of Yarnell Street and the Foothill Freeway (30). These cracks imply breaking along a northeast-trending, high-angle fault which seemed to cut across the thrust sequence (plate 2).

Surface breaks occurred along faults west of Sombrero Ranch house, which was extensively damaged during the earthquake. The principal activity was along a segment of a fault that strikes east and varies in dip along strike from moderately north to steeply south (plate 2). The north side of this fault moved up a maximum of about 5 cm (2 inches) relative to the south side across one ridge crest (31).

Sombrero Canyon to Olive View Hospital area. Additional faulting occurred to the east toward Olive View Hospital, along the projected trace of the eastern Santa Susana fault zone at the base of the steep front of the mountains. The Towsley Formation apparently is overturned progressively to a point at the edge of the mountains where it dips 25° N., suggesting that the fault beneath it has a very gentle dip (plates 2 and 5). To the north, the surface on which the late Miocene and early Pliocene marine sediments* of the Towsley Formation were deposited extends northeast, up along the side of the mountains to the north at least as high as 2700 feet, indicating that uplift of this early Pliocene marine shoreline has been about 900 m (3000 feet) in the western San Gabriel Mountains north of Olive View since early Pliocene time.

The site of the Sunray Oil Company exploratory oil well, Stetson-Sombrero 1, is south of the fault (plate 2). This well was drilled to a depth of 12,027 feet in nonmarine sedimentary rocks, probably mostly of the Saugus Formation. Perhaps these rocks were deposited to such great thickness in a synclinal trough along the front of the range which had begun to develop in early-middle? Pleistocene time. The trough may be represented now by a concealed link between the Mission Hills and Merrick synclines (plate 2). It is probable that the section may be exaggerated in thickness by faulting. A possible structural relationship here is shown in cross-section A-A′ (plate 5). It suggests that the surface on which the Towsley Formation was deposited has been displaced at least 3.5 km (more than 2 miles) to the south by reverse faulting (thrusting).

Offsets of younger, Pleistocene features are not so easy to detect. It is possible that, if terrace-like deposits of older alluvium at the 1750-foot level in the mountains are equivalent to the lower part of the Pacoima Formation (as in the Wilson Canyon area), reverse offset of the base of this formation is at least 225m (750 feet). To distinguish among the Quaternary nonmarine rock units is difficult because of the variability of lithology and the probable disconformity of contacts. For example, north of the western end of Olive View, the Pacoima Formation is composed mostly of constituents derived from the Towsley Formation which caps the basement complex to the north. In poor outcrops, the Pacoima Formation is similar to the Towsley Formation. Deep weathering in exposures of uplifted former surfaces, such as just north of Olive View, causes pebbly conglomerate of different units to look very similar. In addition, the marine-nonmarine boundary between Pico Formation and Saugus Formation may transgress upward from southwest to northeast, further complicating interpretation of structure.

To the east, in the Wilson Canyon area, the Pacoima Formation is derived mostly from dioritic gneiss and related basement rocks; therefore, it is practically identical to younger units of similarly derived older alluvium (Barrows, this Bulletin).

Steeply dipping tension faults lie to the north of the concealed trace of the eastern lower Santa Susana fault between Sombrero Canyon and the Olive View Hospital area. One such fault between Sombrero and Hog Canyons was active during the earthquake (32). Further to the east, fault-like cracks cut the crests of three adjacent ridges just north of the eastern lower Santa Susana fault (33). These breaks may be similar to stronger breaks north of the principal reverse faults of the Tujunga and Lakeview segments to the east (plate 3), but no conformable breaks were found along the apparent trace of the eastern lower Santa Susana fault in this vicinity.

Continuing eastward toward Olive View, a well-defined reverse fault dipping about 45° N. across the ridge west of Schoolhouse Canyon clearly has placed contorted rocks of probable Pico Formation of Middle Pliocene age over younger north-dipping Pacoima Formation of probable middle Pleistocene age (34). Cross fractures, slight upward bowing, and landsliding along the fault on the west side of the canyon suggest, at least, that shaking was intensified along it (photo 4). The fault extends across a powerline road cut in bedrock along the ridge crest here, but the road had been regraded before it was observed the day after the earthquake by Allan G. Barrows; and it is not known whether displacement occurred in the road.

The area from Schoolhouse Canyon east to Wilson Canyon, north of Olive View, was mapped slightly differently from Merifield (1958) or as adapted by Jahns and others (1968) and Proctor and others (1972). The present mapping resembles more closely that of Union Oil Company (1953). Along the east side of Schoolhouse Canyon, fossiliferous sandstone, probably of the Pico Formation, is clearly thrust over Pacoima Formation; and intense landsliding along the fault suggests that it was active here in 1971 or that shaking was intensified. Further east, a small fault break extends 45 m (150 feet) over two ridges; this fault strikes east, dips 75° S., and on the eastern end brings Towsley or Pico Formation up over older alluvium or Pacoima Formation (36). Maximum measurable displacement in the earthquake was about 2 cm (0.8 inch) (photo 5).

The principal north-dipping fault continues eastward and northeastward, apparently at least to a point near where a relatively new water tank, partly on fill, was severely shaken and damaged (38). This fault was mapped as the northeast segment of the Olive View fault by Merifield (1958); but, for this report, the segment is considered as the easternmost part of the lower Santa Susana fault. The fault may die out in bedding of the Pacoima Formation or beneath alluvium. To the northwest of the tank, faults trend north to northeast, similar to the Sombrero fault and others that angle off into the basement complex (plate 2). The nearly continuous trend of a zone of marble layers of the Placerita Formation into this area from at least 2 miles to the northwest suggests that only small offsets occur along these north- to northwest-trending faults.

The name Olive View fault is applied to the fault zone that lies between the eastern lower Santa

* This is Oakeshott's (1958) Elsmere Member of the Repetto Formation. . . Editor

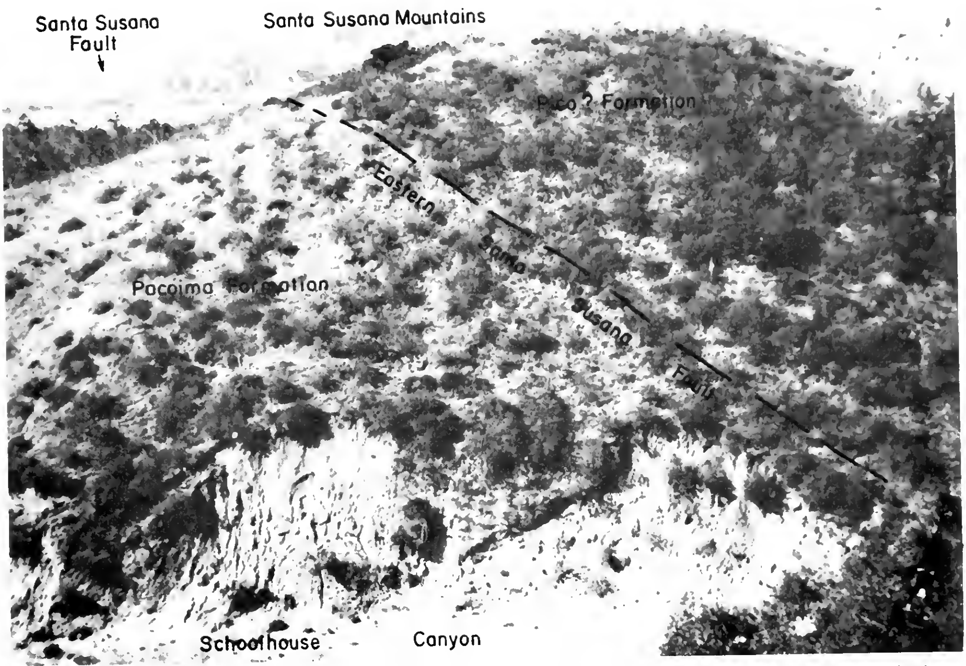


Photo 4. View west-southwest, about 300 m (1000 feet) north of western end of Olive View Hospital property (locality 34). Eastern lower Santa Susana fault dips about 45° N. through ridge on west side of Schoolhouse Canyon. Highly folded, fractured, and overturned (?) sandstone, probably Pico Formation, is thrust over relatively undisturbed, north-dipping conglomerate of Pacoima Formation. Small cross fractures, slight warping, and landslides along trace where shown on side of ridge suggest slight activity along fault in this area. From bottom of canyon to top of hill is about 40 m (125 feet) vertically.

Photo 5. View south showing western part of fault break which is about 370 m (1200 feet) north of western edge of Olive View Hospital complex (locality 36). Break strikes N. 80° E. for about 45 m (150 feet) and dips 75° S., with a maximum reverse offset during earthquake of 2 cm (¾ inch). At most easterly point of break, fault clearly shows Pliocene Towsley or Pico Formation displaced northward over Pleistocene Pacoima Formation or older alluvium.

Susana fault and the most northwesterly buildings of the Olive View Hospital complex (plate 2). This fault zone is best exposed in Schoolhouse Canyon and just west of Wilson Canyon. Between the canyons, the principal fault is best defined as a vegetational lineament visible on aerial photographs. All along its trace, this fault has such suggestions of earthquake activity as thin cracks across ridge tops, a bent pipe where the fault apparently extends into Wilson Dam, and cracks across asphalt pavement and in the Olive View laundry building (plate 3). At the southwestern end, a small fault on the east side of Schoolhouse Canyon shows slight displacement, and several cracks that extend for about 60 m (200 feet) southwest of the canyon may be along a southwest extension of a fault of this zone (35). Where best exposed in Schoolhouse Canyon and just west of Wilson Canyon, faults of the Olive View fault zone dip moderately to steeply north, with Pacoima Formation on the north side overriding older alluvium on the south side (plates 2 and 5). Both the Schoolhouse Canyon and Wilson Canyon Dams were damaged during the earthquake. The area of Wilson Canyon and to the east is described in this Bulletin by Barrows.

Photo 6. View west-southwest from 75 m (250 feet) east of main building of Olive View Hospital (locality 40). Crack visible in foreground is down on south as much as 1 cm (0.4 inch). Brunton compass for scale.

Photo 7. View east at southwest corner of Olive View Hospital main building; ground cracks formed as a result of spreading out and bowing up of fill to south of building, probably in response to movement of fill beneath building during shaking and collapse of south stairwell (barely visible). *Photo by James E. Kahle.*

Olive View Hospital area. The badly damaged Olive View Hospital complex lies at the southern edge of the foothills of the San Gabriel Mountains, partly on alluvium and partly on artificial fill (plate 2). There are known faults in the vicinity, especially in the foothills to the north of most of the buildings; and it is possible that intensified shaking and small displacements may have occurred along some of them during the earthquake (as discussed previously). It is not clear whether faults are present immediately south of the foothills; but a topographic scarp along the hills just to the south of the most easterly buildings east of Wilson Canyon, with Pacoima Formation and older alluvium seemingly uplifted to the north, gives the appearance of a fault scarp or fault-line scarp (Barrows, this Bulletin).

No definite evidence was found to show that a fault lies here although ground cracks (up slightly on the north) east of the east parking lot (lot J) of the main hospital building may represent surface expression of possible faulting (40) (photo 6). However, a south-trending magnetometer traverse here revealed only a very small magnetic anomaly, and a traverse several hundred feet to the east showed no anomaly suggestive of a buried fault scarp, as is common across known fault scarps elsewhere in the earthquake area (Chapman and Chase, this Bulletin).

The new Olive View Hospital buildings were designed in 1964 to meet earthquake code changes of that year. Construction was completed in 1970. All four buildings were badly damaged: The main building, which moved slightly north and east, was severely damaged, with three of its four stairwells falling over; and the psychiatric building moved south and east (a walled embankment lay to its north) and collapsed.

The buildings were constructed partly on artificial fill and partly on younger alluvium, which is probably more than 30 m (100 feet) deep at the mouth of Wilson Canyon (plate 2). The younger alluvium consists of relatively coarse, essentially unconsolidated sand and gravel deposited by the stream in Wilson Canyon before a flood control dam was built there. The fill on which the main hospital building was constructed seems to have failed at least partially (photo 7). Many tensional and compressional cracks and other surface features developed in asphalted areas and over such buried structures as the east-west Maclay High (water) Line aqueduct of the Los Angeles City Department of Water and Power. These features were mapped by James E. Kahle and Allan G. Barrows in March 1971 and are shown in the vicinity north of (39).

Most investigators have concluded that the buildings at Olive View were damaged by strong ground motion and not by faulting. Regarding the main building, Frazier and others (1971, p. 142) stated that it is ". . . doubtful if the hospital could have taken another 5 seconds of shaking." Whether one or more faults extend east-northeastward or west-northwestward through or beneath the new hospital area is speculative as far as present knowledge is concerned. Even if such faults do exist, it is speculative whether even slight displacement at depth did occur and whether displacement or other activity did enhance or exaggerate ground shaking at the surface in the area. Monitoring of aftershocks in the earthquake area was attempted by Warrick and Joyner (1971, p. 91–96) to determine the degree of shaking in different rock types, but results were only partially successful. It seems reasonable, however, that shaking of fill or unconsolidated younger alluvium would be relatively greater than consolidated or cemented sedimentary deposits.

Small, older buildings north of the new buildings were constructed mostly on younger alluvium. Most were not damaged extensively and still are usable. Older buildings in the western area were constructed partly on older alluvium, partly on fill derived from older alluvium, and partly on younger alluvium (37). Although it is difficult to distinguish the exact boundaries of these three types of material here, areas of fill seem to have been especially susceptible to failure by sliding, presumably caused by shaking. Fills for the Foothill Freeway in the area also failed by sliding caused by shaking.

Southeast of the Olive View area is a zone comprised of two segments of relatively strong street cracks and lesser ground cracks, which extends southeast in alluvium for about 1 km (3300 feet) from just southeast of Bledsoe Street to Polk Street (41). The zone is interpreted as a possible fault break which may follow the trend of bedding of the Saugus Formation beneath the alluvium. The zone is nearly parallel to the strike of the two closest exposures of the Saugus Formation to the north and south (plate 2). The zone lies along the northern edge of a small, northwest-trending secondary bulge in the generally west-trending zone of maximum change in elevation during the earthquake (figure 3). Houses along the zone were damaged.

Geologic evidence does not seem to indicate that a zone of intensified shaking lies specifically along the front of the San Gabriel Mountains from the Olive View Hospital area east to the Veterans Administration Hospital area. As has been proposed elsewhere, such a zone would extend east from Olive View through the area of Almetz and Aldergrove Streets where houses were badly damaged (see also Steinbrugge, this Bulletin) (43), but the severe damage here was to split-level houses with bedroom-over-garage plan (Slosson, this Bulletin; Steinbrugge, this Bulletin); and split-level houses also were badly damaged on Fenton Avenue between Tyler and Polk Streets (42), which is about a quarter to half a mile south of the mountains and south of the zone suggested. In the east end of the zone, the houses that were badly damaged southeast of the Veterans Administration Hospital were of two-story design (46). The building code of the City of Los Angeles does not provide for differences in construction between one- and two-story houses. Additional bracing could have prevented many total losses of these houses according to Frazier and others (1971, p. 290).

Many of these badly damaged houses were built partially or wholly on artificial fill. The relationship of damage to house design and building site was not analyzed for this report. To do this, the sites for all houses of a specific design in a tract should be classified as bedrock, younger or older alluvium, or partially or wholly artificial fill. Other factors could then be related: orientation of the house on its site and its orientation relative to the epicenter, to the regional slope angle, and to the estimated attitude of bedding in bedrock at surface or below alluvium or fill.

Northwestern Sylmar

The northwestern side of the Sylmar inlier of the San Fernando Valley constitutes a belt of serious economic loss from damage in the earthquake. The belt includes, from roughly northeast to southwest, damage to the Foothill and Golden State Freeways and their interchanges, the San Fernando Juvenile Hall of the County of Los Angeles, the Southern Pacific railroad bed and tracks, the Pacific Intertie Terminal (including the Sylmar Converter Station), Upper San Fernando Dam and Van Norman Reservoir of the Los Angeles City Department of Water and Power, the Joseph P. Jensen Filtration Plant of the Metropolitan Water District, the Van Gogh School (Saul, this Bulletin), residences, and other buildings. The estimated cost of repair and replacement of damaged structures and apparatus in the area was more than $50 million (Steinbrugge, this Bulletin).

The surface effects and damage within this belt lie along a northeast-trending alluvial area which contains not only the trace of the concealed Mission Hills syncline but a zone of probable faulting, most of which also is concealed. Most of the buildings and other structures damaged were constructed at least partly on fill over younger alluvium, which in this area ranges from silt and fine sand to relatively fine gravel. At the south edge of the area, Upper San Fernando Dam is abutted in north-dipping beds of the Saugus Formation. A facility of Bendix Corporation constructed on Saugus Formation and fill slightly southeast of the belt of damage was not damaged severely.

The Mission Hills syncline is concealed but extends into the area from the southwest, probably towards the Sombrero Ranch area (plate 2). Steeper dips, generally to the southeast, suggest that the axial plane of the syncline dips southeast. In addition, one or more faults are believed to extend through the area: J. C. Hazzard, for Union Oil Company (1953), projected a branch of the Santa Susana fault northeast through the area from its bedrock exposures to the southwest; Merifield's work (1958) delineating faults was adapted by Jahns and others (1968) and further modified after the earthquake by Proctor and others (1972).

Surface breaks from the earthquake in this area included many ground cracks, sand boils, cracks in concrete and asphalt, and shattered earth on ridges in low foothills to the northwest underlain by the Saugus Formation. Ground cracks were widespread in the area, in natural ground and in fill. From southwest to northeast, they occurred locally as follows: abundant pavement cracks in the Van Gogh School area and ground cracks a fourth to half a mile north of the school (11); cracks in the fill for the Joseph P. Jensen Filtration Plant (10); bank failures and sand boils in the northern part of Van Norman Reservoir (13); and curvilinear ground cracks which extend from northeast of San Fernando Juvenile Hall southwest into the Pacific Intertie Terminal area (14). There were other ground cracks northeast of the Juvenile Hall in the area of Herrick Avenue and Yarnell Streets (26), at the west end of Norris Street (29), and scattered sparsely to the east of the Juvenile Hall toward Roxford Street (28).

The strong curvilinear cracks to the northeast of the Juvenile Hall extended southwest at least 900 m (nearly 3000 feet) to the Pacific Intertie Terminal in a zone as wide as 450 m (nearly 1500 feet) (photo 8).

Photo 8. View northeast from front parking lot of San Fernando Juvenile Hall shows severe damage to building. It also shows northwest margin of ground cracking caused by shaking and consequent movement of ground in right part of photograph to southwest toward camera. Cracks in foreground show right-lateral displacement; those on opposite end of parking lot (off the right side of photograph) show left-lateral displacement. *Photo by James E. Kahle.*

The cracks within an olive grove northeast of the Hall clearly showed vertical displacement downward on their concave sides (27). This implies that the ground inside either settled downward during shaking or lurched or slid southwestward at an angle of slightly less than 1°, even though maximum slope of the ground surface in the area more toward the south or south-southeast is at an angle slightly greater than 1°. Further evidence of lurching or sliding is that man-made features within the perimeter of cracking are displaced right laterally on the northwest side and left laterally on the southeast side (15). Also within the perimeter, the Southern Pacific railroad tracks were bent compressionally.

Such strong features of ground cracking in moist fine-grained sandy alluvium, along with development of sand boils at the surface, imply that liquefaction of sub-surface strata occurred during shaking, causing gravitational lurching or sliding. Structures built on the ground, thus, were damaged by a combination of shaking and ground movement.

Detailed studies of the relationship of the geologic features of the earthquake to damage in the Juvenile Hall-Pacific Intertie area have been made by Youd (1972, p. 105–109) and by Smith and Fallgren (this Bulletin). A discussion relating damage to geology was provided by Scott (1971, p. 299–331).

The ground failure of the Juvenile Hall and Pacific Intertie area was described as a landslide by Youd (1971, p. 105–109), who stated that the ". . . movements were of landslide origin, predominantly by lateral spreading . . ." He also stated that surveying data along San Fernando Road would allow very small left-lateral tectonic displacement of a possible northeast-trending fault through the Juvenile Hall area, although the displacements which he observed in the Juvenile Hall area were much larger. In a later abstract, Youd (1972) stated that the results of his study "establish" that the down slope movements, as large as 5.7 feet, were of landslide origin.

Three soil types are included within the Juvenile Hall area of ground cracks according to the small-scale map of soils of the San Fernando Valley prepared by Holmes and others (1917). Most of the soil in the area is classified as Yolo loam; the more southerly area is Yolo sandy loam; a small area at the northeast is Hanford silt loam; and the area of cracks is bordered on the southeast by Dublin clay loam. The Yolo loam is said by Holmes and others (1917) to be ". . . easily penetrated by roots and water and retentive of soil moisture." Thus, the Yolo loam would seem to be ground that might be subject to liquefaction during intense earthquake shaking.

The alluvium slightly southwest of the Southern Pacific railroad tracks is known to be at least 41 m (135 feet) deep, as a California Division of Highways drill hole to that depth did not reach bedrock. The depth to the ground water table is less than 3 m (10 feet) southwest of the tracks and deepens to the northeast (Brown, this Bulletin). The water table deepens to 7.5–9 m (25–30 feet) near the northeast edge of the Juvenile Hall ground cracks. Trenches (T 9, T 10, and T 11) dug across cracks in the Juvenile Hall area were examined by Allan G. Barrows and James E. Kahle. The trenches showed cracks descending to moist gravelly layers and layers of moist silty sand from depths of 1.7 m (5.5 feet) to at least 2.7 m (9 feet), the greatest depth of the trenches (photos 9 and 10).

Southwest of the Juvenile Hall area, the cracks seem to diminish in strength at the flood control channel at the northeastern edge of the Pacific Intertie Terminal (15). Southwest of the channel, the strongest effects may lie in alluvium beneath fill, which here extends to Van Norman Reservoir and around its north edge (plate 2). These effects may extend to the surface south of the fill as numerous sand boils, which were noted in the north part of the lake bottom after the reservoir was partially drained. On the other hand, these sand boils may have been caused by subsurface effects unrelated to ground cracks to the northeast, or they may have been caused by intense sliding of the bank around the north edge of the reservoir (photo 11).

Photo 9. View north; ground cracks in yard of San Fernando Juvenile Hall. Cracks resulted from sliding and settling along wet, sandy layers of alluvium during shaking. Strongest cracks did not extend beneath floor of trench (T9). Close-up view shown in photo 10. *Photo by James E. Kahle.*

Photo 10. Close-up view of east side of trench in photo 9 showing cracks. *Photo by James E. Kahle.*

Upper San Fernando Dam also was intensely shaken and moved horizontally south 1.5 m (5 feet) and slumped 0.9 m (3 feet) as reported by Duke (1971, p. 228–229) and by Scott (1971, p. 302–314). North-dipping, reverse faults in older alluvium and Saugus Formation just southeast of the dam apparently were not active during the earthquake (plate 2). Small landslides did occur in the area, however; and shattered earth was found on at least one ridge south of the dam (plate 3).

Farther southwest, strong cracks developed in the fill for the Joseph P. Jensen Filtration Plant (10). Damage to the plant, which was under construction, was attributed by Marachi (1972) to "liquefaction of a layer of saturated silty sand alluvium at a depth of about 15 m (50 feet)"; the compacted fill also settled. Acceleration here was estimated at about 0.4 g

Photo 11. View south shows landslide in west side of small peninsula extending out into Upper Van Norman Reservoir; this area is part of fill at north edge of reservoir which failed (locality 13, plate 3). *Photo by James E. Kahle.*

in a statement by H. J. Mills, general manager of the Metropolitan Water District, reported by Duke (1971, p. 226). Strong north-northeast-trending cracks also developed west of the fill in natural ground west of Balboa Boulevard (11); at least some of these cracks were down on the east. They seemed similar to the cracks in the Juvenile Hall area, except that they were not curvilinear.

A relationship between surface breaks in the Juvenile Hall-Van Norman Reservoir area and possible faulting cannot be discounted entirely. Faulting in bedrock in the area may have extended up into the alluvium and possibly amplified the shaking, or some of the breaks may represent the surface effects of faulting.

Evidence for prior faulting in the northwestern alluvial area of the Sylmar inlier is based partly on projection into the area of faulting in bedrock to the northeast and southwest and partly on geomorphic evidence. A fault was mapped in the Olive View Hospital area and named the Olive View fault by Merifield (1958), who projected it southwest just north of Van Norman Reservoir.

Merifield's work was modified by Jahns and others (1968), who delineated a North Olive View fault as well as the Olive View fault of Merifield, both projected southwestward from bedrock in the northwestern Olive View area. The North Olive View fault was projected southwest about to the 1399-foot elevation benchmark at Foothill Boulevard. This projection was made on the basis of a relatively abrupt 20–25 m (70–80 foot) change upward in the ground water level from southeast to northwest as determined by a drilling program along the route of the proposed San Fernando tunnel. This work was further modified by Proctor and others (1972), who projected the North Olive View fault about 1 mile farther southwest and modified the location of the Olive View fault to bring the two faults nearly parallel to the strong ground cracks northeast of the Juvenile Hall (plate 3).

In earlier work of Union Oil Company (1953), J. C. Hazzard extended a branch of the Santa Susana fault into this area from the southwest.

Aerial photographs of the region show at least two apparent fault lines trending northeastward in the area of the Juvenile Hall. The more southeasterly of these lines is extended on plate 2 southwestward beyond its photographic lineament to an abrupt bend in the Grapevine Creek drainage, now covered by fill for the Pacific Intertie Terminal (plate 2). Most of the ground cracks which developed north-northeast or northeast of San Fernando Juvenile Hall were at least slightly curvilinear, suggesting that they were not breaks along faults; but two 2-story houses at the west end of Norris Street were severely damaged where ground cracks occurred, implying intense shaking there (29). As well, the photographic lineaments do not seem to lie exactly along the trends of any of these cracks, although the lineaments are not precise linear features but rather zones commonly of narrow but indeterminate width.

Further geomorphic evidence of possible faulting and relatively recent Quaternary uplift of hills north of the alluvial area consists of abrupt changes in stream gradients at the mouths of Grapevine and other nearby canyons, with resultant fan deposits.

Surveying data in a report by the Office of the Los Angeles County Engineer, Surveying Division, (1972) implies that horizontal displacements in the western Sylmar area during the earthquake were generally to the south and southeast, averaging 9–12 cm (0.3–0.4 feet) in the San Fernando Pass region. Elevation change data made available to the Division by the Los Angeles City Surveyor show that vertical increases in elevation in the Sylmar area gradually diminished to the west from a maximum of 2.47 m (8.1 feet) near Pacoima Wash channel to about 0.3 m (0.9 feet) just west of the Juvenile Hall area. This change implies that the general intensity of tectonic activity dies out to the west, as does the general intensity of surface effects (figure 3).

Ground breaks in the Saugus Formation just northwest of the belt of damage were probably fault breaks (16), which are essentially parallel to the lower Santa Susana fault to the northwest.

It is also possible that the Mission Hills syncline through this area was further developed during the earthquake. A trend of decrease in vertical elevation changes lies along the southeast edge of the syncline (figure 2), as a similar effect occurred along the Merrick syncline (Barrows, this Bulletin).

San Fernando Fault Zone

The San Fernando fault zone is similar to other roughly west to west-northwest trending, north-dipping reverse fault zones of the Transverse Ranges of southern California. The Verdugo fault is a part of this system and may extend, concealed from the southeast, toward the San Fernando zone near Mission Hills. The Mission Hills fault, concealed just south of Mission Hills, may be part of the San Fernando zone or the Verdugo zone.

The principal faults of the San Fernando zone dip north irregularly at the surface, from 20°–25° N. to vertical, suggesting that the fault planes may be rather sinuous. Preliminary interpretation of seismic data by Whitcomb (1971, p. 30–32) suggests that the principal fault plane affected by the earthquake dips about 45°–50° north (also, see Bolt, this Bulletin). Preliminary fault plane solutions also were made by Dillinger and Espinosa (1971, p. 142–149) but were less conclusive about the dip.

In the Sylmar area, fault traces of the San Fernando zone generally lie along the contacts between the Modelo Formation of middle-late Miocene age and the Towsley and Pico Formations of very late Miocene to middle Pliocene age (plate 2). These rocks are commonly folded near the fault zone but dip moderately north over-all. They are succeeded generally north of the zone by the thick nonmarine sequence of the Saugus Formation, including its Sunshine Ranch Member of estuarine origin. The Pacoima Formation (Oakeshott, 1952) overlies the Saugus Formation disconformably in the foothills of the San Gabriel Mountains, and the lithologic constituents reflect a change in source area for these fluviatile deposits (Barrows, this Bulletin). The two principal folds in the Sylmar area are the Mission Hills anticline in the Mission Hills and the Mission Hills syncline just north of the Mission Hills.

Reservoir segment. The Reservoir segment is named after the Reservoir fault, perhaps the most prominent fault to have been delineated in the southern Mission Hills before the earthquake (Union Oil Company, 1953). The segment seems to comprise literally a tangle of faults much more complex than along other parts of the zone (plate 2), but this unusual complexity is probably more apparent than real because the rocks in the southern Mission Hills area, especially on the east side of former Lower Van Norman Reservoir, have been widely exposed in cuts for freeways and roads; thus a complexity of faulting has been disclosed which is not uncommon in such cuts elsewhere in the region. In addition, trenches and cuts for geologic exploration by the Los Angeles Department of Water and Power dug along the edges of the former reservoir also disclosed many pre-earthquake faults (as mapped by Saul, this Bulletin, plate 2).

Pre-earthquake faults of the Reservoir segment apparently extend concealed northeast into the Mission Hills through the area of the site of Lower San Fernando Dam and toward the Mission Wells segment. Faults of the zone were mapped in the area by Kew (1924) but not extended to the northeast; they were mapped in greater detail, especially from excellent exposures along cuts for old Sepulveda Boulevard by Union Oil Company (1953). Part of the zone also was mapped by Oakeshott (1958). Faults of the zone dip both north and south, and dips along individual faults vary. For example, the dip of the most southerly fault ranges from 35° south to nearly vertical just from old Sepulveda Boulevard (Blucher Avenue) 75 m (250 feet) eastward to the west side of the San Diego Freeway.

The principal tectonic rupture in the zone, which is the strongest and best-documented rupture near Lower San Fernando Dam, lies at the north edge of the

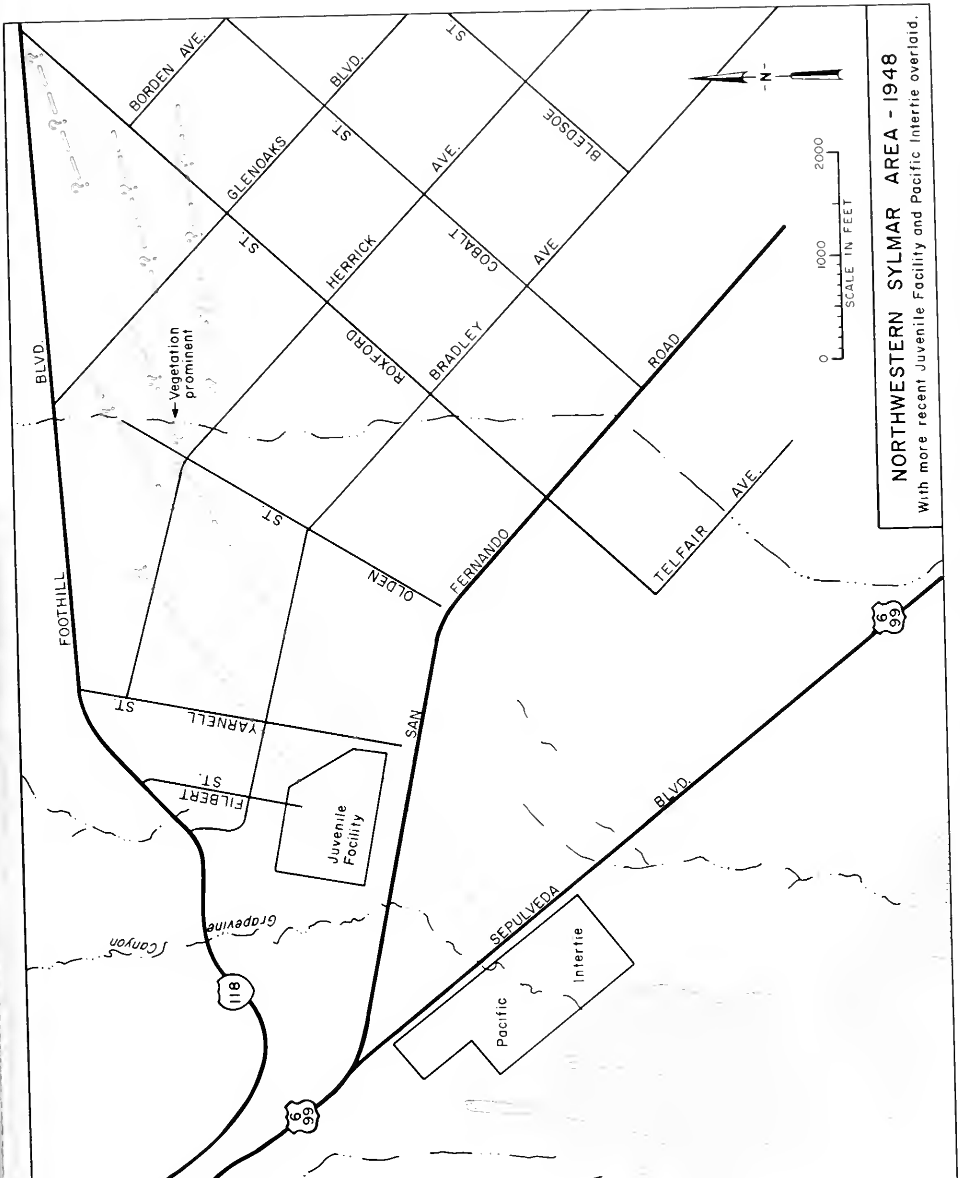


Figure 1. Lineaments interpreted from aerial photographs are traces of probable (dashed) and possible (queried) faults which extend mostly concealed across alluvial area of northwestern Sylmar. Photomap is drawn from 1948 photograph with Juvenile Hall and Golden State Freeway of later years added. Development of cracks and intense shaking in area may be partially related to possible subsurface activity along these probable and possible faults (see plates 2 and 3).

Reservoir segment, where it occurred wholly in man-made cuts (58). This east-trending, north-dipping fault displayed both reverse and left-lateral sense of movement where it broke the Golden State Freeway. On the east edge of the San Diego Freeway, successive concrete drain segments for a distance of about 90 m (300 feet) north of the fault were overthrust south at the seams a total of about 20 cm (8 inches) (photo 12).

Photo 12. View north showing principal break of Reservoir segment of San Fernando fault zone where it cuts across the San Diego Freeway about 300 feet south of collapsed southeast-bound bypass bridge of Golden State Freeway. Broken pavement here was repaired soon after photograph was taken on morning of earthquake and was not examined by Division of Mines and Geology. Later examination of area showed that seams in concrete drain along east side of freeway from fault break north about to site of collapsed bridge had cumulative southward compression of approximately 8 inches (20 cm). *Photo courtesy of the California Division of Highways.*

Surface effects also suggested that several other faults of this segment were active during the earthquake, if only because of possible intensified shaking along them; such shaking may have caused slight displacement and landsliding in artificial cuts. For example, a prominent fault that strikes northeast and dips north was displaced slightly upward on its south side in the west cut of the San Diego Freeway. Prominent cracks along this fault extended northeast away from the east cut of the freeway for about 30 m (100 feet) across a flat, artificially cut surface (57). Additionally, a minor bedding-plane fault with displacement is at the north end of the west cut. A crack also extended across Blucher Avenue (old Sepulveda Boulevard) between roadcut exposures of a fault, and repair here of a pipeline extending along the avenue suggested activity along the fault (55).

There may have been displacement along a southeast-dipping bedding plane fault which extends southwest from the west edge of Blucher Avenue, west of the Division of Highways station (56). Here, the contacts of a clayey fine-grained sandstone or siltstone layer within a conglomerate sequence of the Sunshine Ranch Member of the Saugus Formation seem to have been shaken and displaced. The rocks above the clayey layer appear to have moved slightly upward to the north.

To the east of this break, the asphalt cover for the fill at the Division of Highways maintenance station was cracked; a landslide developed in the west part of Blucher Avenue, trending toward Lower Van Norman Reservoir. Damage in this small area was minimal.

Fault breaks along the trend of bedding of the Saugus Formation elsewhere in the epicentral area may be similar secondary effects of intensified shaking (see also Saul and Barrows, this Bulletin).

There is no evidence that major fault rupture extended to the Lower San Fernando Dam which partly failed by sliding northward into the reservoir, though prior mapping by Kew (1924) shows concealed faults beneath younger alluvium on which the hydraulic fill for the dam was placed (Cortright, this Bulletin). However, a small break relatively close to the dam was mapped by Saul (this Bulletin) (52). Cracks without displacement developed in bedding at the top of the ridge 245 m (800 feet) east-northeast of the east abutment of the dam (51). Surficial landsliding occurred west of the cracks above the edge of a prominent cut, and rocks fell off the cut toward the reservoir during the earthquake. Landsliding also occurred along the edges of a ridge directly south of the east abutment. The recorded ground acceleration nearest to the dam was at 8244 Orion Street, about 7 km (4⅜ miles) south; maximum vertical acceleration there was .28 g (Maley and Cloud, 1971, p. 165; Cloud and Hudson, this Bulletin).

Northwest of the Reservoir segment, a group of surface breaks extended northwestward toward Van Norman Reservoir. These breaks were essentially parallel to the bedding of the Saugus Formation, which underlies much of the area; and one such break seemed to be essentially along the northeast-dipping contact between the upper member of this formation and the lower, Sunshine Ranch Member (plate 2) (59). Where it crossed part of the concrete surface of the Golden State Freeway as a crack, this fault break showed small reverse and left-lateral displacement; and where it extended northwest beyond the concrete into a low cut, it became a mole track.

The second relatively prominent surface break cut a ridge capped by thin older alluvium southwest of the Golden State Freeway (61). The break seemed similar to those which lay 5½ km (3⅓ miles) to the east in the Harding School area. The strike of the break was northwestward, essentially parallel to the underlying Saugus Formation. It was about 135 m (about 450 feet) long, with the north side down a maximum of about 15 cm (6 inches). Near the northwest end, a mole track lay just southwest of the principal cracks. There were many additional surface effects of the earthquake south and southeast of this break. They included ground cracks, severe cracking and settling of the fills for the freeway, and cracking of a concrete channel west of the freeway (60) (photo 13).

Northwest of these breaks, there was a small break in the Saugus Formation at the southeast end of a debris basin (62). West of this locality, at least two pre-earthquake faults were exposed in a Los Angeles Department of Water and Power trench which

Photo 13. Compressional breaks in southeast-bound lanes of Golden State Freeway bypass, approximately at contact between fill to right and cut in Saugus Formation to left. View south also shows slide mass of Lower San Fernando Dam in now-empty reservoir in right background. Small landslides formed in hill in left background, and rocks fell from bare cut during the shaking.

lay just south of the eastern abutment of Upper San Fernando Dam (plate 2). Both are reverse faults which strike northwestward and dip moderately northeastward essentially parallel to bedding in the Saugus Formation which underlies the older alluvium here. Although these faults apparently were not active during the earthquake, the more southerly one may demonstrate 3 m (10 feet) or more of reverse offset of the contact between the Saugus Formation and older alluvium. It also seemed to have a slight south-facing, pre-earthquake scarp along it at the top of the trench. The more northerly fault had only 0.4 m (1.3 feet) offset in a prominent sand layer in the older alluvium; but, at the top of the trench, a wedge of soil and slope wash that extended down into the fault suggested relatively recent pre-earthquake activity.

Mission Hills and Verdugo faults. The totally concealed Mission Hills fault was mapped by Oakeshott (1958) at least partially on the basis of evidence from exploratory oil-well data. Additional, more recent data strongly suggest that a high-angle reverse fault extends along the south edge of the Mission Hills toward the possible northeast extension of the Verdugo fault (plates 2 and 5). Alluvium just south of the Mission Hills thickens abruptly to 75 m (250 feet) or more according to cross-section E–E' of plate 5B of California State Water Rights Board (1962), probably indicating considerable later Quaternary movement along the fault which caused the present Mission Hills to form north of it.

Reverse displacement on the Mission Hills fault just east of the Golden State Freeway is indicated by a cross section of Union Oil Company (1953). This cross section, which was updated recently by the company to account for the latest exploratory well data, shows about 1200 m (4000 feet) of reverse displacement of the boundary between the upper Mohnian and Delmontian Stages of the upper Miocene.

The Verdugo fault may extend concealed into the area from the southeast. On plate 2 of this Bulletin, the fault is extended along a ground water cascade plotted by the California State Water Rights Board (1962, plate 30 and others). Southeast of the Mission Hills, major vertical offset along the Verdugo fault and perhaps the Northridge Hills fault zone has dropped the basement rocks in the San Fernando Valley area 5500 m (18,000 feet) relative to the basement rocks in the highest part of the Verdugo Hills to the north (interpreted from Corbato, 1963). Offset along these and related faults must decrease northwest from the Verdugo Hills toward the Sylmar area, however, for the highest elevation of the basement rocks decreases northwestward from the top of the Verdugo Mountains (3077 feet) to the Pacoima Hills (1294 feet) and to the Mission Hills. Wells drilled to about minus 9000 feet in elevation in the Mission Hills area have not reached basement.

The Verdugo fault also is considered to be a high-angle reverse fault which dips north, although it dips 70° south where the California State Water Rights Board (1962, p. A-23) observed it cutting Quaternary older alluvium near Burbank.

Surface breaks apparently did not occur along the Mission Hills and Verdugo faults during the earthquake but structures approximately along the trace of the concealed Mission Hills fault did sustain considerable damage. Included was structural damage to the modern Holy Cross Hospital (built in 1950) and the nearly new Indian Hills Medical Center, both multistoried buildings (54). Alemany High School and the Rinaldi Street overpass of the San Diego Freeway also were damaged. Fills for the freeway spread inward 2–3 cm (1+ inches) toward Rinaldi Street from both the north and south directions as measured from offset sidewalks (50). The cracks in the sidewalks on Rinaldi Street beneath the San Diego Freeway were repaired after the February 9 earthquake but reopened slightly during the March 31 aftershock, when Alemany High School was damaged again.

No permanent ground displacement was observed by the writer in this area, although numerous cracks in asphalt parking lots and in curbs could be observed in the area of the high school and the hospital and at the Farmers Insurance Building, about a block south on Sepulveda Boulevard. Ground shaking appears to have been relatively strong in the area, judging from extensive cracking of pavement there. With regard to damage, Frazier and others (1971, p. 214) stated, "The Indian Hills Medical Center Building demonstrates that the minimum building code requirements for this type of structure lead to extensive damage when the ground motion has a peak acceleration in the range of 30% to 40% g."

A group of tensional and compressional cracks formed in the western corner of the city of San Fernando (70). Most were in streets; some were in curbs and sidewalks; and a few broke the ground surface. These cracks may be related to possible faults in bedrock which is roughly 14–45 m (50 to 150 feet) beneath the alluvium here. Strike of the cracks was northwest to east-northeast. Possible faults along these trends are indicated on plate 2 even though the cracks do not seem to have consistent patterns of offset. It is also possible that the cracks and damage were related to shaking of wet sandy layers of alluvium, but this does not seem likely. A shopping center, older houses, schools, and churches were damaged. The cracks extended toward downtown San Fernando where many older unreinforced buildings were badly damaged; but, in the downtown area, only minor cracking in pavements could be observed (71).

The Pacoima Hills fault (Oakeshott, 1958) is a north-dipping fault with basement complex on the south and Tertiary sedimentary and volcanic rocks in the Pacoima Hills north of the fault. It was examined for surface expressions of activity during the earthquake, but none was found (77). Neither were such effects found along the projected trace of the Verdugo fault south of the hills. Preliminary surveying data compiled by the Los Angeles County Engineer, Survey Division, (in press) show that the ground in the hills at triangulation station "Pacoima 2" apparently moved relatively south-southwest 0.78 m (2.54 feet) during the event.

Mission Wells segment. The Mission Wells break of the San Fernando fault zone seems to be a southwest extension of the dramatic ground breaks of the Sylmar segment to the northeast (plate 2). Actually, the Mission Wells segment may be a more southerly fault en echelon with the fault breaks of the Sylmar segment. The Mission Wells break demonstrated both left-lateral and reverse offset along nearly its entire length from Osceola Street northeastward to the Southern Pacific railroad tracks.

The bedrock geologic relationships of the Mission Wells segment are best exposed on the north side of Osceola Street, just west of Rossiter Avenue (69). Here the fault dips about 60° N. and places north-dipping Saugus Formation over Modelo Formation which strikes east, parallel to the fault, and dips south (plates 2 and 5). South facing scarps along a mole track of the break in backyard lawns northwest of Osceola Street were as high as 12 cm (5 inches). At 14901 Osceola Street, part of a concrete patio was uplifted on the north about 15 cm (6 inches) and thrust south about 20 cm (8 inches). Left-lateral offset along the segment was probably no more than 2–3 cm (about 1 inch) and showed curbs bowed very slightly.

There was damage along the fault to houses, a trailer park, Osceola Street School, streets, and public utilities. Two houses on a bedrock cut northwest of Osceola Street, under which the fault broke, were so severely damaged that they required demolition. In contrast, most houses on older alluvium under which the Mission Wells break apparently passed have been repaired.

The relationship between the Mission Wells segment and faults of the Reservoir segment is not exactly clear. The Mission Wells fault may extend south-southeast beyond where its surface break dies out, or it may extend to the southwest toward the Reservoir fault segment.

Between the Mission Wells and Sylmar segments, a slight pre-earthquake rise in slope can be observed, such as on Ralston Avenue across a field northeast of the Southern Pacific railroad tracks (figure 4) (68). The area north of the interval between the Mission Wells and Sylmar segments rose at least slightly in elevation during the earthquake according to surveying data (figure 3; Burford and others, 1971, p. 81), even though there apparently were no ground breaks.

The Mission Wells segment died out at the railroad tracks, just about where the Sylmar notch (opening) in the ground water impediment described by the California State Water Rights Board (1962) reaches its greatest depth, about 15 m (50 feet). It may be coincident that a fault rupture did not occur at the surface between the Mission Wells and Sylmar segments; but more reasonably, probable faulting in the bedrock dissipated into the thicker alluvium here before reaching the surface. The Sylmar "notch" apparently extends from slightly west of San Fernando Road to about Fourth Street just southeast of Hubbard Street. Within 75 m (250 feet) north of the notch, bedrock lies 5 m (15 feet) or less beneath the surface; whereas, within about 150 m (500 feet) south of the notch, the depth to bedrock increases to 20 m (65 feet) or more as interpreted from cross sections of the California State Water Rights Board (1962, plate 5H). A parr of the probable buried fault scarp east of the railroad tracks also has been delineated by a magnetic anomaly (Chapman and Chase, this Bulletin), exactly along the projected extension of the fault break mapped to the west.

The Mission Wells segment may extend east to Meyer and Lazard Streets in San Fernando, where cracks occurred (76). Thus the segment may extend concealed eastward toward the more southerly fault break in the San Fernando Industrial Park (88), rather than northeast toward the Sylmar segment.

Even though the exact geologic relationships along the Mission Wells and Sylmar segments are not clear, a strong hypothetical fault trending north-northwest as postulated by Merifield (1958, figure 5) does not seem necessary to account for the apparent offset in the contact between the Saugus Formation and older rocks as projected east from the Mission Hills and west from the Pacoima Wash area. Hypothetical concealed contacts between formations shown on the accompanying geologic map (plate 2) suggest a reasonable stratigraphic and structural match of the rocks underlying the alluvium between the Mission Wells segment and the San Fernando Industrial Park to the east without such a cross fault.

Sylmar segment. The fault breaks which make up the Sylmar segment of the San Fernando fault zone comprise some of the most spectacular effects of faulting in the earthquake region. These breaks extend east-northeast from near Hubbard Street and Glenoaks Boulevard across a portion of the most heavily populated part of Sylmar and San Fernando to just east of Pacoima Wash channel. The breaks include a swath of ground cracks, mole tracks and cracked, broken, and compressed pavement, sidewalks and curbs as much as 275–360 m (900 to 1200 feet) wide, depending on the limits of what is considered faulting (photos 14, 15, 16, and 17).

Photo 14. Badly damaged shopping center and bowling alley on southwest side of Glenoaks Boulevard at Hubbard Street; buildings razed since photograph taken. View west, about 215 m (700 feet) southeast of Hubbard Street, shows fault break of Sylmar segment extending across asphalt parking lot as weltlike feature; in foreground, portion of concrete sidewalk was thrust about 50 cm (20 inches) south; underground utility lines and storm drain in Glenoaks Boulevard to right were extensively damaged, as were businesses to right out of view.

Photo 16. Surface break of Sylmar segment of San Fernando fault zone extends northwest along edge of Foothill Boulevard toward houses and modern apartment building (photo 15). In foreground, concrete driveway and its asphalt approach to boulevard were broken into short segments which were successively overthrust. In February 1972, house next to site of apartment was jacked-up, and a new foundation was constructed beneath it; severely damaged middle house was unoccupied.

Photo 15. Severely damaged and leaning modern apartment building, now razed, formerly at southeast corner of Foothill Boulevard and Harding Avenue (locality 81). View northeast. Fault break of Sylmar segment extended through corner of building in far carport and crossed Harding Street to right of camera point. Building was constructed on older alluvium.

Photo 17. View west across Newton Street showing scarp about 30 cm (12 inches) high along fault break of Sylmar segment of San Fernando fault zone. Break extends into southwest edge of house which was later razed. Most houses along fault break in this neighborhood have been razed; most houses on southern side of fault were not badly damaged, but houses on north (up-faulted) side were generally badly damaged, though repairable. Houses partly or wholly on fills in this area commonly were damaged by the effects of shaking.

There was extensive damage along the Sylmar segment to shopping centers and other businesses at Glenoaks Boulevard and Hubbard Street, to many residential houses, to a modern apartment building, and to the Foothill Freeway, as well as to streets and utility lines and to two buried flood control channels. A gas line along Glenoaks Boulevard burst in several places where breaks of the segment crossed it.

The most obvious social effects of faulting along the segment could be seen a year after the earthquake. Rehabilitation of a small, badly damaged modern shopping center on Glenoaks Boulevard had only just begun. The Boys Market at the corner of Glenoaks Boulevard and Hubbard Street was under reconstruction using reinforced brick on a new fill which had replaced an older one (78). At one site where a fault break cut through a single-family dwelling, the house had been razed and a new one had been constructed partly on the obvious fault scarp. The badly damaged modern apartment building, through a corner of which the fault passed, had been razed; and the resulting vacant lot had no apparent trace of a fault in it (81). Other houses had been removed. The Foothill Freeway, with a spectacular bend added to it during the earthquake, had not been repaired (83). Between Maclay Avenue and Newton Street, every house had been razed along the path of the main break. Sewer lines and streets still were under repair. To the southeast, most of the badly damaged commercial buildings of the San Fernando Industrial Park had been repaired and were being used again.

The most westerly breaks of the fault segment were on the southwest side of Hubbard Street, about 230 m (750 feet) southwest of Glenoaks Boulevard, and in front of The Gables (a convalescent hospital). Diagonally across Hubbard Street to the southwest, there were compression features in asphalt curbing; but no trace of a fault break was apparent (75). To the east-northeast along the zone, near the San Fernando-Sylmar boundary, the segment narrowed and bent slightly to trend almost due east. Just east of Pacoima Wash channel, a single break bent southeast along the base of the curve in the hills and apparently died out although a break along the same trend to the south in the San Fernando Industrial Park was probably along the same fault (plate 2). Southeast and east from the indusrrial park, the fault breaks are part of the Tujunga segment (Barrows, this Bulletin).

The details of faulting along the Sylmar segment during the earthquake have been reported especially by geologists of the California Institute of Technology (Kamb and others, 1971, p. 41–54) and the U. S. Geological Survey (1971, p. 55–76; Sharp, this Bulletin; and Bonilla, 1972 and in press).

Fault breaks of the segment demonstrated left-lateral, normal (vertical) and shortening (thrust) components of faulting. For example, on the principal break in younger alluvium just east of Newton Street, a fence was offset left laterally 30 cm (12 inches); vertical offset (down on the south) was also 30 cm (12 inches) (T5). On Cometa Avenue in San Fernando, the major southerly break showed curbs offset left laterally 1.15 m (3.7 feet) and the ground surface down vertically on the south side 23 cm (9 inches). Shortening to the south of the southwest sidewalk along Glenoaks Boulevard at the southern periphery of the fault segment was about 50 cm (1.6 feet). In addition to damage, these displacements have created surveying and legal problems for re-establishment of property lines (Ellingwood and Williamson, 1971; Mitchell, 1971). Horizontal displacements along the Sylmar segment, as measured by geodetic surveying methods, reached at least 1 m (3.18 feet) (Los Angeles County Engineer, Survey Division, 1972, figure 10).

The fault breaks of the segment lie along the front of a group of relatively young, low hills which consist of older alluvium overlying north-dipping beds of the Towsley/Pico Formations and the Saugus Formation. This older alluvium is bouldery and relatively coarse grained; it is derived from the gneiss and other igneous-metamorphic rocks present in the San Gabriel Mountains to the north. It lies as a veneer of perhaps 3 to 10 m (10 to 35 feet) in average thickness and is similar to the older alluvium which lies partially draped over the Mission Hills to the southwest. It is probably similar to much of the older alluvium above the bedrock surface of the entire Sylmar inlier of the San Fernando Valley. A southeasterly trending magnetometer traverse across Hubbard Street just southwest of Glenoaks Boulevard delineated a strong anomaly across the fault zone probably caused by a change in the character or thickness of the magnetite-bearing alluvium (Chapman and Chase, this Bulletin).

Subsurface expression of the fault segment was relatively obscure where alluvial materials underlie ground breaks: especially young, unconsolidated sand and gravel, such as on the east side of Newton Street. Hardly a trace of the fault could be observed here in the walls of a trench dug by the Division of Mines and Geology across a prominent scarp (T5, plate 3). In a trench (T13, plate 3) examined by James E. Kahle, which was dug by the Division into more consolidated older alluvium just northeast of the Foothill Freeway, a primary fault break dips 50°–55° N. Bedding of the Towsley/Pico Formations to the west on Gladstone Avenue and slightly north of the fault break strike parallel to the fault and dip 55°–60° N. (figure 2, plate 2). Older, moderately consolidated alluvium in the sides of a large trench dug to repair the badly broken, buried flood control channel on Eighth Street, between Gridley and Fernmont Streets, seemed to show little or no evidence of faulting below mole tracks of the faulr segment which extended to the edge of the trench (80). Nearby, a narrow, more accessible trench to replace utility lines along Knox Street, just southeast of Orange Grove Avenue, showed a similar lack of geologic expression where a mole track was exposed in lawns on both sides of the street.

The principal trend of maximum elevation increase in the Sylmar area during the earthquake extends east from the intersection of Glenoaks Boulevard and Hubbard Street to a point just south of Lopez Dam in Pacoima Wash (figure 3). The trend lies essentially along the north edge of the Sylmar segment. The point surveyed by the City of Los Angeles which had the greatest rise in elevation is about 180 m (600 feet) north of where the principal fault of the segment crossed Newton Street (84). This rise was 2.47 m (8.1 feet). On the east end of the trend, the intersection of Glenoaks Boulevard and Hubbard Street rose nearly 1.5 m (5 feet), from an elevation of about 1179 feet to about 1184 feet; whereas to the southwest about 410 m (1350 feet), the intersection of Hubbard Street and Herrick Avenue rose only 0.12 m (0.4 feet) from its previous elevation of 1149 feet. This rise in elevation (up-dip to the north) of the principal reverse faults of the Sylmar segment suggests that the ground surface here bowed upward slightly during the earthquake (figure 2). Thus a sense can be gained of how the area of older alluvium north of the principal faults has begun to "grow" into hills during faulting during earthquakes.

The Tujunga segment extends west into the San Fernando Industrial Park area and seems to split, with one branch extending north toward the Sylmar segment and another branch extending slightly north of west. The west-trending branch demonstrated left-lateral reverse displacement; and, judging by a south-sweeping bend up onto a small rise where the grade for the uncompleted Foothill Freeway had been prepared, the fault may dip very gently north there (88). This branch extended west-northwest as a mole track

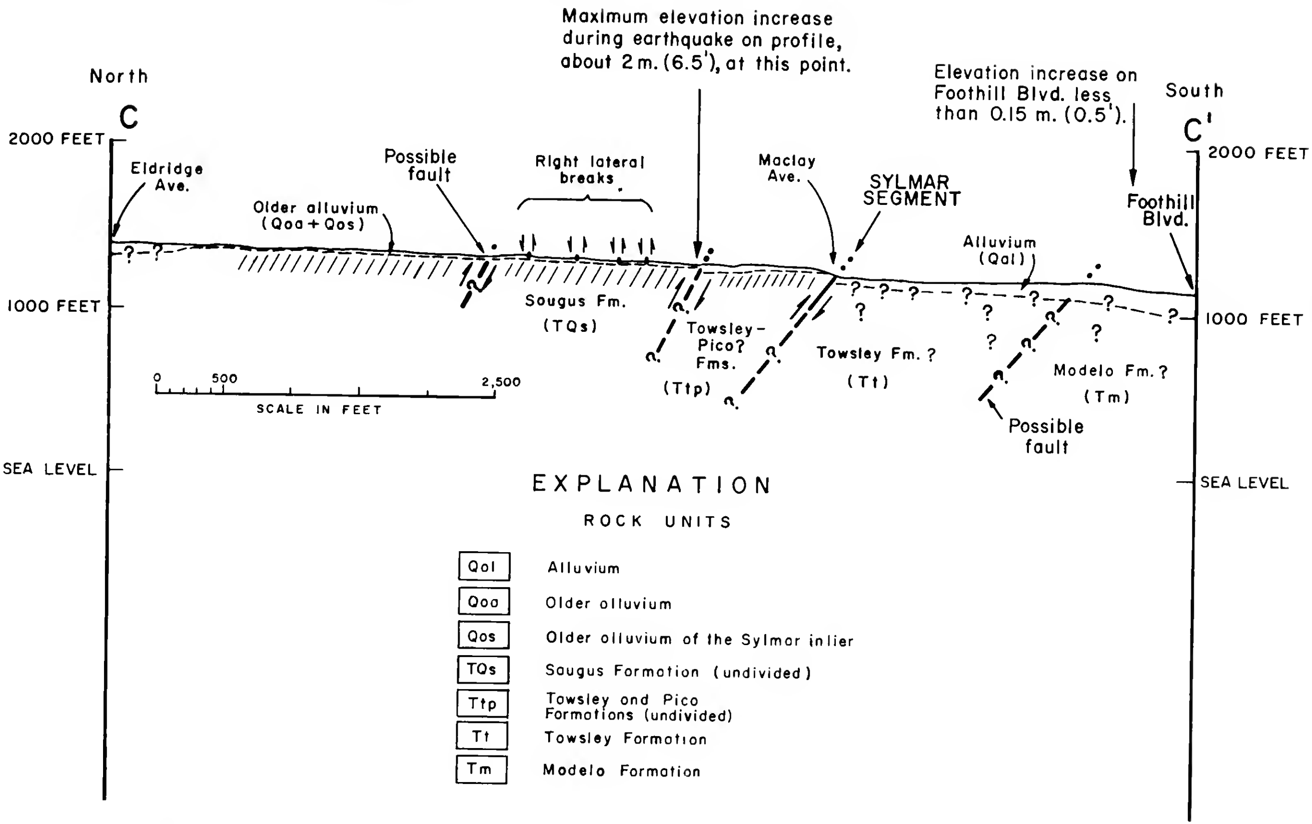


Figure 2. Cross section extends from north to south at a point about 300 m (1000 feet) east of intersection of Foothill Boulevard and Maclay Avenue. Faults are essentially along bedding of north-dipping clastic sediments of late Miocene to early(?) Pleistocene age. Offset of contact between bedrock and older/younger alluvium along faults is partly surmised.

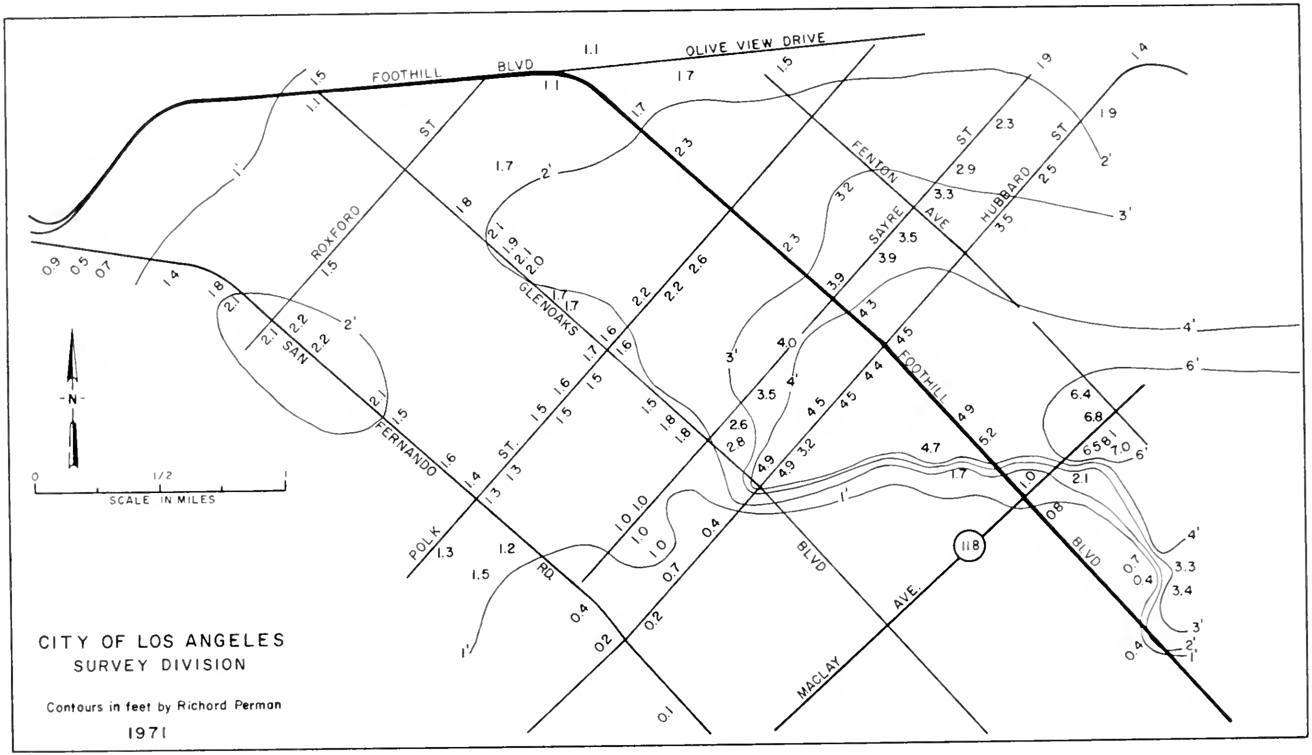


Figure 3. Trend of maximum elevation rise during the earthquake extends from near the intersection of Glenoaks Boulevard and Hubbard Street to beyond the area to the east at a point just south of Lopez Dam in Pacoima Wash. This trend is essentially parallel to the fault breaks of the Sylmar segment, about 250 m (800+ feet) north of the south edge of the segment. The point of maximum elevation rise (8.1 feet) in the Sylmar area lies 125 m (400+ feet) south of the intersection of Maclay and Fenton Avenues. The two-foot trend in the northwest part of the area shown lies along the southeast flank of the Mission Hills syncline.

with parallel tension cracks north of it through a field which once was part of Pacoima Wash before a channel was built for it. The fault break could not be traced west of the channel; but, if the fault does extend concealed to the west, it may trend toward the east end of the Mission Wells segment, perhaps generally along the concealed contact between the Modelo and Towsley Formations (plate 2).

Considerable damage occurred in the San Fernando Industrial Park, where many of the light industrial buildings were constructed of concrete tilt-up walls and panelized plywood roofs. In the eastern part of the Park, a fault break seems to have extended through the California National Guard building, which sustained very little damage; this building is reported to have been built according to Field Act standards. The degree of shaking in the area was suggested by a resident directly across Foothill Boulevard from the large scarp west of the site for the former Foothill Nursing Home (90); he stated early the morning of the earthquake that, when he came out of his house on the south side of the boulevard, people in cars who stopped there after the shaking had blood on their faces, suggesting the degree to which they, and possibly their automobiles, had been tossed around.

North of the Sylmar segment. There was a prominent group of fault breaks, street cracks, and broken curbs 300 to 600 m (1000 to 2000 feet) north of the eastern part of the Sylmar segment, in the Harding School area and vicinity. The fault breaks strike slightly north of east and seemed to fan out slightly to the west, away from the trend of the Sylmar segment. Though the breaks occurred in relatively thin older alluvium, they probably strike parallel to bedding of the underlying Saugus Formation, similar to a break to the west at locality 61 near the site of former Lower Van Norman Reservoir.

The most southerly of these breaks was exposed in the Foothill Freeway (82) (photo 18); this fault broke very slightly left laterally and down slightly to the south at the northeast edge of the freeway. In the northeast freeway cut, the fault seemed to dip steeply north with total pre-earthquake reverse displacement of perhaps 30 m (100 feet) or more of the very gently north-dipping angular unconformity between the Towsley/Pico/Saugus sequence (Plio-Pleistocene) and the overlying older alluvium (Pleistocene).

The faults north of the one exposed in the freeway are on the north side of the trend of maximum elevation change (85). These breaks were offset vertically and downward to the north, commonly accompanied by small right-lateral displacements.

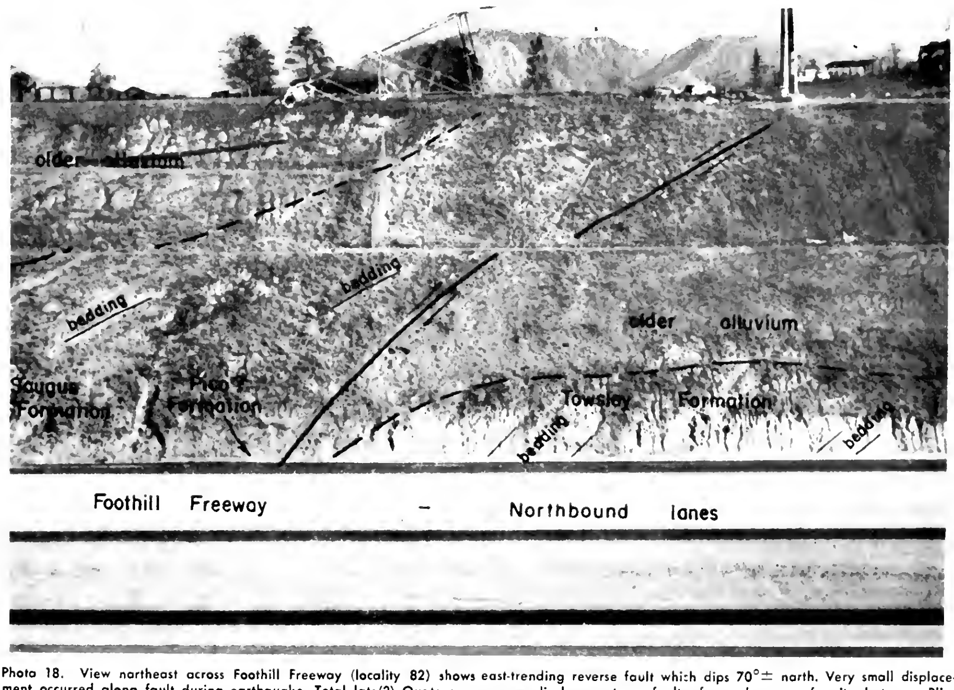


Photo 18. View northeast across Foothill Freeway (locality 82) shows east-trending reverse fault which dips 70°± north. Very small displacement occurred along fault during earthquake. Total late(?) Quaternary reverse displacement on fault of angular unconformity between Pliocene sedimentary rocks and Pleistocene older alluvium here is estimated to be about 30 m (100 feet). Power line tower was not toppled by earthquake.

Houses, Alta Mesa Convalescent Hospital (formerly Highland Sanitarium), and Harding School were damaged. At least one of the faults extended east into the base of Lopez Dam, which was damaged. Where the trace of one of these breaks was observed in a small cliff just west of Lopez Dam, the ground seemed to contain an abundant growth of pre-earthquake vegetation, but a nearly horizontal unconformity exposed there of Saugus Formation overlain by older alluvium has essentially no appreciable pre-earthquake offset. These breaks may reflect tension release within bedding planes of the Saugus Formation. Rocks to the north of the west trend of maximum elevation rise are step-faulted down to the north to reflect decreasing change in elevation in that direction (figures 2 and 4).

A lesser trend or "nose" of elevation increase swings northwest from near Hubbard Street and Fenton Avenue and extends toward the Olive View Hospital area according to data of the Los Angeles City Surveyor (figure 2). A third trend extends west from near the intersection of Hubbard Street and Foothill Boulevard to near the intersection of Tyler Avenue and Borden Street, then southeast to San Fernando Road between Roxford and Bledsoe Streets, following a 0.6 m (2 foot) maximum contour.

The detailed topography of the 1953 U. S. Geological Survey map of the San Fernando quadrangle shows several fault scarps in the Sylmar area (figure 4). The topography clearly shows the scarp of the main Sylmar segment from the Pacoima Wash area at least as far west as Orange Grove Avenue and suggests that the scarp has a maximum height of at least 7.5 m (25 feet). It also seems to express the scarp of the fault exposed in the Foothill Freeway for a distance of at least 1200 m (4000 feet) and perhaps 1800 m (6000 feet). The map also shows the trace of a possible third fault to the north, which would also have a south-facing scarp (plate 2). Surface cracks along this third apparent fault trace do not seem to indicate faulting, however (86). The map also was useful in differentiating the uplifted and dissected older alluvium from the younger alluvium in this area, as shown on plate 2.

Central Part of the Sylmar Inlier

The area in the central part of the Sylmar inlier was considerably damaged, but the damage was not easily related to the tectonic features of the earthquake. For example, in the area immediately west of the intersection of Hubbard Street and Foothill Boulevard, shopping centers, Sylmar High School, a large apartment building (Friday USA) at 12960 Dronfield Avenue (79), and an enclosed reservoir at Hubbard Street and Dronfield Avenue were damaged. The area lies along a trend of elevation increase (figure 3), but faults that lie to the east did not break this far west. No permanent ground cracks were seen although street cracks through this area commonly trend west. Some of them were compressional and accompanied broken curbs and sidewalks.

Two strong compressional breaks in the Foothill Freeway at Astoria Street and compressional effects to the southeast along Foothill Boulevard in this area could not be linked directly to faulting.

The geology of the nearly flat surface of the Sylmar inlier of the San Fernando Valley is of interest because much damage from the earthquake occurred on it; yet, most of it was not faulted, although bedrock beneath alluvium may have been faulted. The bedrock surface of the inlier was formed by erosion before it was covered by bouldery late(?) Pleistocene and Holocene alluvium. The surface north of the fault zone is in the initial stages of uplift and erosion, as the area east of Pacoima Wash is in a similar but more advanced stage.

The gently south-dipping, nearly flat surface of the Sylmar inlier is within the same general (275 to 425 m, 900 to 1400 feet) elevation range as similar mountain and hill front surfaces elsewhere in this region that are covered by veneers of alluvium or colluvium. Examples of such surfaces include the eastern Simi Valley area and parts of the Thousand Oaks area. These surfaces seem beveled and uplifted similar to known 400,000-year-old marine terraces as high as 400–425 m (1300 to 1400 feet) in the coastal Palos Verdes Hills and Ventura areas. No marine deposits have been found on the interior surfaces, but perhaps estuarine deposits have been overlooked. The very northern edge of the Sylmar surface is about 490 m (1600 feet) in elevation, about the same as that of Horse Flats and other uplifted areas to the west.

The intensity of surface effects in the central part of the Sylmar area may be related at least partly to the thickness of the alluvial cover above the Saugus Formation which is presumed to be present at depth here. Younger and older alluvium probably thicken generally from east to west, averaging 7.5 to 15 m (20 to 50 feet) thick according to cross sections of the California State Water Rights Board (1962, plate 5B). In the north part of the Sylmar area, the alluvium reaches depths of 60 m (200 feet) according to cross sections of a report by Jahns and others (1968). Where possible fault activity in bedrock extends upward to the surface in alluvium, surface cracks and damage may reflect trends of faulting below as in the vicinity of Eldridge Avenue and Sayre Street (87). Many street cracks in the flat part of Sylmar seem to trend parallel to the general strike of the Saugus Formation below the alluvium, but this could not be proven. Generally, the local abundance and intensity of street cracks and broken curbs reflect the intensity of local damage, but no exact relationship to this pattern could be established.

A possible fault break comprises a zone of street cracks west of Sylmar High School, northeast of Herrick Avenue (74). At 14733 Lakeside Street, a ground depression extended across the front yard and into the house, where there was a crack in the concrete porch base. This zone was mapped tentatively as a fault break (plates 2 and 3).

Southwest of this feature lies the Sylmar Industrial Park in the vicinity of Bledsoe Street and Bradley Avenue, where several buildings were structurally damaged during the earthquake (65). Abundant cracks in asphalt streets and parking lots, broken curbs, and severe cracks in buildings were seen here. A few of the cracks could be traced into the ground, especially

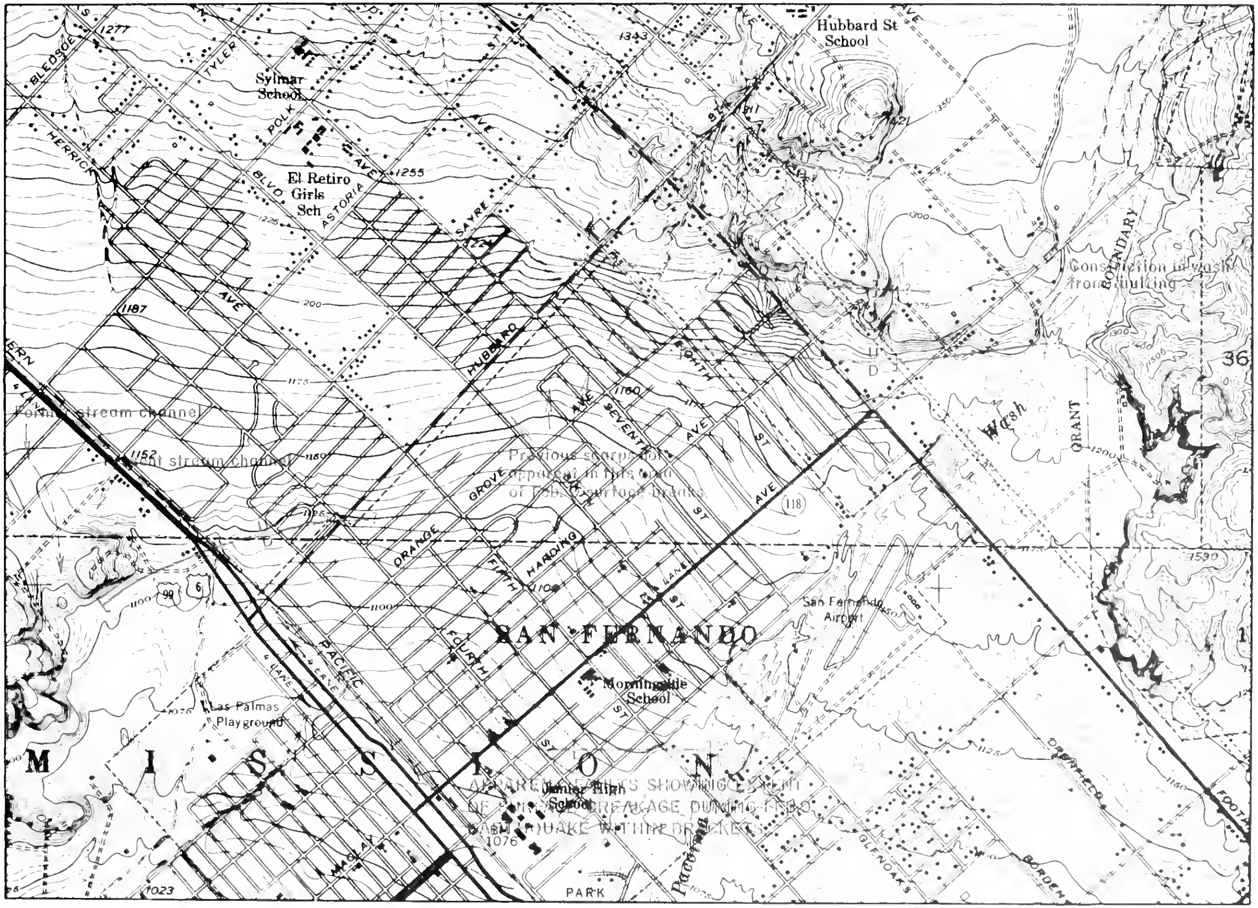


Figure 4. Apparent fault scarps previous to February 9 earthquake are plotted along sharp to gentle linear breaks in slope, as defined by pattern of contours. Map is portion of 1953 edition of San Fernando quadrangle (topography by plane table methods, 1924–1934); newest, 1966 map has 10- and 40-foot contour intervals and does not delineate scarp features as well. Fault north of Sylmar segment had minor displacement during February 9 earthquake (see also photo 18); and second postulated fault north of Sylmar segment had no apparent surface breakage.

Contour intervals = 5 feet and 25 feet. Base map by US Geological Survey those along San Fernando Road northeast of the railroad tracks near Tyler Street. One remote but perhaps related ground crack trending northwest was observed in a wash between San Fernando Boulevard and Cobalt Street (63). The dominant trend of the street cracks of the Sylmar Industrial Park is southwestward into the El Dorado School area (66). The cracks in the Industrial Park and School areas generally showed no vertical offset, but some did show left-lateral displacement. The reason for the cracks in the area is not known; perhaps they are related to liquefaction of soils during shaking and involving concealed fault activity.

There were relatively strong street cracks and damaged houses in the vicinity of Cobalt Street and Dronfield Avenue in the younger alluvium, but they could not be related to faulting (72); similar street cracks and damage in the vicinity of Sayre Street and Eldridge Avenue may be related to possible fault activity at depth (87). A strong break across Astoria Street just northeast of Garrick Avenue was probably formed by the effects of compaction or compression during shaking in a small fill for part of the street there (44) (photo 19).

Photo 19. Compressional break in sidewalk, parking, and curb of Astoria Street about 30 m (100 feet) northeast of Garrick Avenue (locality 44). View is northwest, nearly half a mile southwest of Veterans Administration Hospital. Feature does not extend beyond street area and therefore probably cannot be attributed to faulting; more likely it was caused by the shaking of the earthquake, perhaps acting on a relatively weak fill in this portion of the street. House was not badly damaged.

At two localities, older, pre-earthquake street cracks seem to have been reactivated during the earthquake: Bledsoe Street, just north of Glenoaks Boulevard (73) and Roxford Street, north of Bradley Avenue (64). Perhaps these cracks were caused originally by settling of the ground surface caused by compaction of the alluvium.

Street cracks do not seem to be related generally to soil types in the alluvium. In the area called "San Fernando La Cienega" by the California State Water Rights Board (1962), there was relatively little damage and little street cracking. This area lies along San Fernando Road from just west of Oro Grande Street, east to about the intersection of Herrick Avenue and Hubbard Street (67). The area was judged by the California State Water Rights Board (1962), on the basis of the calcium carbonate content of its soil, to have had a very high water table (1.2 m (4 feet) below the surface) before water was first removed intensively for agriculture many years ago. If the water table had been close to the surface during the earthquake, damage probably would have been much greater.

CONCLUSIONS

The San Fernando earthquake affected the very northern edge of the heavily populated portion of the Los Angeles region. Although the earthquake resulted in death and injury to people and more than $500 million in damage, the results of a similar 6.4 magnitude event in a slightly more densely populated portion of the region could have been far more devastating. As a lesson from only partial disaster, the earthquake has offered a unique opportunity to study its geologic effects relative to the damage in the Sylmar area.

To go along with the good luck of having the earthquake occur at 6:00 a.m., it was also good luck that none of the severely damaged hospitals lay directly over a fault that ruptured during the earthquake. Generally, where single-story houses and small commercial buildings stood along faults that ruptured, they were severely damaged; where similar buildings stood near the severely damaged hospitals, they were not severely damaged.

To study the spectacular geologic effects along the principal earthquake faults is scientifically important, but serious damage in this earthquake occurred in many areas apparently with little relationship to faulting. A pragmatic field method for better relating the cause of widespread damage to the geologic and seismic effects is needed; such a method could result in a Mercalli-type map prepared without interpreting nongeologic effects. The map would tie the effects of faulting and ground shaking to the areal geology and thus create a better guide for planning in an area affected by an earthquake, as well as in other areas. The features utilized in making such a map would range from mundane street cracks to spectacular fault breaks and would include such shaking effects as shattered soil, landslides, and even the effects on certain plants (like prickly pear cactus, the leaves of which tend to break off).

In addition, accelerographs should be placed on a wide variety of rock types and geologic environments just after a main earthquake. Thus, data on shaking during aftershocks could be analyzed and related to the over-all geologic environment and the pattern of damage.

Earthquake Effects on Rock Types

No analysis was made in the Sylmar area to relate surface features to individual geologic units. The relationship of landsliding and other surface features to formations east of the Sylmar area has been discussed by Morton and by Barrows (this Bulletin).

The Saugus Formation seems to be prone to minor faulting along certain clay-bearing layers, and the faults of the San Fernando zone are essentially along bedding planes and formational contacts of the upper

Table 1. Selected exploratory wells in the Sylmar area. Data mostly from California Division of Oil and Gas (1964; 1972, personal communication).

Plate 2 location symbol	San Bernardino Base and Meridian	Operator	Well No.	Date started	Total depth (feet)	Bedrock stratigraphy
A	Sec. 19, T. 3 N., R. 15 W.	Richfield Oil Corp.	"T. I. & T." 1	Nov 1943	8207	Saugus Formation: surface to 8207 feet.
B	Sec. 21, T. 3 N., R. 15 W.	Sunray DX Oil Co.	"Stetson-Sombrero" 1	Mar 1950	12027	Saugus Formation: from base of alluvium to 12027 feet.
C	Sec. 30, T. 3 N., R. 15 W.	Sunray DX Oil Co.	"T. I. & T." 1	May 1942	8035	Upper member, Saugus Formation: surface to 2050 feet; Sunshine Ranch Member: 2050–4200 feet; Porter oil-bearing zone: 7280 feet; bottom of hole: Pliocene.
D	Sec. 2, T. 2 N., R. 15 W.	Pacoima Petroleum & Helium Gas Corp., Ltd.	1	Oct 1924	2700	Modelo Formation: probably from base of alluvium to 2700 feet.
E	Sec. 4, T. 2 N., R. 15 W.	Gulf Oil Corp. of California	1 "Carey"	Mar 1956	10136	Upper member, Saugus Formation: surface to 4570 feet; top of Sunshine Ranch Member: 4570 feet; top of Repetto Formation (essentially equivalent to Towsley Formation): 6470 feet; top of Delmontian foraminiferal zone: 7780 feet; bottom: late Miocene.
F	Sec. 4, T. 2 N., R. 15 W.	Shell Oil Co.	"Mission" 1	May 1923	4953	Mohnian foraminiferal zone: 400 to 3213 feet; bottom: late Miocene.
G	Sec. 4, T. 2 N., R. 15 W.	Shell Oil Co.	"Mission" 2	April 1928	5687	Mohnian foraminiferal zone: 300–5687 feet; bottom of hole: late Miocene.
H	Sec. 4, T. 2 N., R. 15 W.	Standard Oil Co. of California	Rinaldi core hole	June 1964	4725	Bottom of hole in middle Mohnian foraminiferal zone: late Miocene.
I	Sec. 6, T. 2 N., R. 15 W.	Gulf Oil Corp. of California	"Panorama" 1	Dec 1948	9614	Top of Repetto Formation (essentially equivalent to Towsley Formation): 5500 feet; top of Puente Formation (essentially equivalent to Modelo Formation): 7740 feet; bottom: Miocene.
J	Sec. 10, T. 2 N., R. 15 W.	Occidental Oil Corp.	"Pacoima EH"	April 1968	9291	Top of Delmontian foraminiferal zone: 4030 feet; top of Mohnian zone: 5920 feet; top of Luisian zone: 8260 feet; bottom: Miocene.
K	Sec. 15, T. 2 N., R. 15 W.	Standard Universal	No. 1	April 1926	5938	Bottom in Miocene.
L	Sec. 18, T. 2 N., R. 15 W.	Standard Oil Co. of California	"Woo" 1	Oct 1949	9739	Top of basalt: 8694 feet; top of middle Miocene: 8819 feet; bottom in Topanga Formation, middle Miocene.

Miocene-lower Pleistocene section.

Artificial fills commonly failed by seismic compaction and lateral spreading. Cracks developed in artificial fills at many localities ranging from large fills for freeways to small house pads.

Need for Geologic Mapping

The geologic mapping that was a part of this study resulted in a partially successful attempt to differentiate varieties of older and younger alluvium. Differentiation of these units is necessary if the Quaternary geologic and seismic history of southern California is to be fully understood. The work also has illustrated that all vintages of aerial photographs and topographic maps are useful in relatively large-scale mapping. Use of geophysical methods, ground water knowledge, trenches, and water and exploratory oil well data are also necessary to study faulting properly.

The post-earthquake mapping showed that, in an area populated by more than 50,000 people, with a very large capital investment and relatively well-studied geology, a great deal was not known. This is partly because of the complexity of the geology and the need for larger-scale study, partly because some of the work was done before artificial cuts yielding exposure of critical geologic features were made available and because not all of the knowledge had been collated into a single basic map or group of maps.

Faulting

Age. Slightly west of upper Sombrero Canyon, the surface on which the lower beds of the Towsley Formation (late Miocene or early Pliocene) lie unconformably on crystalline rocks may be thrust more than 3.5 km (more than 2 miles) south on the north-dipping eastern end of the Santa Susana fault. The sea cliff that probably marked the edge of the inland advance of the marine deposits was uplifted at least 900 m (3000 feet) from its former sub-sea level elevation. In the Olive View area, the eastern Santa Susana fault places marine beds of Pliocene age over the Pacoima Formation of middle(?) Pleistocene age.

Reverse-fault displacement of the surface on which the Pacoima Formation may have been deposited is perhaps more than 225 m (750 feet) to the south.

The north-dipping Olive View fault shows Pacoima Formation(?) faulted-up at least 10 m (30 feet) against older alluvium of late (?) Pleistocene age. In the Foothill Freeway north of the Sylmar segment, the angular unconformity between older alluvium and a Pliocene sequence is reverse-faulted at least 30 m (100 feet) vertically. The angular unconformity is along the bedrock surface of the Sylmar inlier. This surface may have been uplifted a maximum of 400-425 m (1300–1400 feet) from sea level during middle-to-late Pleistocene time if the surface is similar to known marine terraces in the coastal area which are uplifted to about that elevation, and in the Palos Verdes Hills are known to be about 400,000 years old.

Pre-earthquake scarps along this fault and the Sylmar and Mission Wells segments are delineated by topography of the 1953 and older San Fernando quadrangle maps of the U. S. Geological Survey, implying that the scarps are relatively young. The apparent scarp along a part of the Sylmar segment may be 8 m (25 feet) or more in height.

Complexity. Large-scale mapping during the present study delineated faults of the area more precisely than previous work, but the fault pattern is complex, as is illustrated by the tangle of faults exposed in freeway and other cuts in the Mission Hills area. The problem of mapping faults is made even greater by a widespread alluvial cover and commonly a gradual change in lithology among the Cenezoic formations that makes differentiation difficult.

Artificially cut ground. Many of the prominent ground ruptures along some faults appeared only where those faults were exposed in artificially cut ground (for example, the principal fault of the Reservoir segment in the Mission Hills).

Possible subtle effects. Ground cracking in alluvium and extensive damage to the San Fernando Juvenile Hall and vicinity from liquefaction during shaking may also be subtle effects of faulting. For example, if faulting in bedrock dissipated upward into alluvium, shaking along the trend of the faulting at the ground surface may have been amplified. Also involved in tectonic activity here may be further folding of the Mission Hills syncline.

Other street and ground cracks on the gently sloping Sylmar inlier also may have resulted from the effects of faulting of various intensities at various depths beneath the ground surface, especially along bedding planes of the Saugus Formation.

The earthquake illustrated a need to understand how the effects of various faulting in bedrock are amplified upward to the surface in alluvium.

ACKNOWLEDGMENTS

The writer acknowledges the collaboration of his colleagues in the preparation of this report, for much knowledge and opinion have been shared through field and office discussions. He also appreciates a discussion of the geology of the area with E. A. Hall, Union Oil Company, who provided valuable data. Field maps by Gordon B. Oakeshott made during his earlier studies in the region were quite useful. The writer thanks the Surveying Division of the City of Los Angeles for a discussion of post-earthquake surveying of the area.

Surface Effects and Related Geology of the San Fernando Earthquake in the Foothill Region Between Little Tujunga and Wilson Canyons

by Allan G. Barrows [1]

ABSTRACT

Surface faulting exhibiting both left-lateral and dip-slip components of displacement along the Tujunga segment of the San Fernando fault zone produced abundant scarps, cracks, and ridges at the base of the foothills between Little Tujunga Canyon and Pacoima Wash. Detailed geological mapping has shown that the Tujunga fault segment of the San Fernando fault zone could have been recognized from natural as well as artificial exposures prior to the earthquake. The measured dip varies from 10° to 50° north along the segment. Trenches across the earthquake scarps revealed a record of previous faulting between alluvial materials and overriding Tertiary sedimentary rocks. In one trench near the mouth of Lopez Canyon, the Tertiary rocks have been thrust over the alluvium more than 13 m (43 feet). Also exposed in this trench is a record of previous faulting of slope wash deposits over alluvium suggestive of very youthful activity along the Tujunga segment.

Within the foothills, surface faulting took place discontinuously along the Kagel fault, along the Oak Hill fault and others that parallel the bedding planes of enclosing strata, and along other minor faults of various orientations. At several places along the trend of the Kagel fault, scarps formed that are not above the actual fault trace itself. They may represent new faults that developed in response to some conditions unique to this earthquake.

Landslides, rockfalls, and other forms of slope failure in the terrain north of the Tujunga segment resulted from severe ground motion and surface faulting. The lithology of the underlying rocks, as well as the steepness of the topography, exerted control over the localization of landslides. Spectacular shattered ridge tops are locally abundant and widespread within the foothill region. These features, which resemble plowed ground, are localized where thin soil or terrace deposits cover sharp ridges or peaks in the underlying sedimentary rocks.

Damage due to surface faulting was restricted to disruption of roads and utilities and affected only a few buildings. Most damage to structures resulted from severe ground movement although landsliding, especially in Kagel Canyon, and surface cracking resulting from differential settlement of artificial fill were responsible for a significant amount of damage.

With the exception of surface faulting on the Veterans fault, numerous slope failures and, locally, shattered ridges, the effects of the San Fernando earthquake on the surficial geology along the mountain front between Pacoima Canyon and Wilson Canyon are rather slight compared to the damage to man-made structures. East of the Veterans Administration Hospital, the well-defined scarp of the Veterans fault can be traced for 300 m (1000 feet) across graded bedrock surfaces parallel to bedding in the Saugus Formation. South of the fault, terrace deposits have been dropped down 4 to 6 m (15 to 20 feet) as a result of previous fault movements. The discontinuous western portion of the Veterans fault can be followed 120 m (400 feet) beyond the clearly developed scarp to Candlewood Drive. Surface faulting, which may or may not be along a continuation of the Veterans fault, is expressed as a low scarp in old alluvial fan deposits west of Candlewood Drive. This fault could be traced to within 390 m (1280 feet) of the collapsed Veterans Administration Hospital.

Between Loop Canyon, north of the Veterans Administration Hospital, and Olive View, no reverse or thrust fault of the Sierra Madre system is exposed between the basement complex and the Pleistocene sedimentary rocks. Certain topographic and structural geologic features in this vicinity are interpreted in this report as implying the presence of a fault along the base of the foothills between Olive View and May Canyon. There was no surface faulting along the trend of this conjectural fault or along the actual contact between the basement rocks and the sedimentary rocks north of the fault.

Since it deals with the geology and surface effects of two areas of unequal size and dissimilar development of surface effects, this paper is divided into two sections. The most convenient dividing line between these two areas is Pacoima Canyon and Wash.

Field work began immediately after the earthquake in the areas of most abundant surface effects, especially where surface breaks due to faulting were concentrated. Initially, mapping of the surface effects was emphasized because these effects are subject to modification or destruction by weather and the activities of man. When most of the effects had been recorded (Barrows and others, 1971), the emphasis shifted to detailed geological mapping so that the observed effects could be related to the underlying geology. The two contiguous areas discussed in this paper comprise about 10 square miles, most of which is east of Pacoima Wash. Mapping was done on aerial photos at scales ranging from 1:2400 to 1:6000. Numbers in parentheses within the text refer to localities in plate 3.

[1] California Division of Mines and Geology, Los Angeles.

Several published and unpublished maps depict the geology of all or a portion of this area at scales as large as 1:12,000. Specific reference to these earlier works is made at appropriate places within the text. Gordon Oakeshott generously provided his very useful original geological field maps of this area. Unpublished data lent by the Union Oil Company were helpful and also appreciated. I benefited from discussions with my colleagues of the Division of Mines and Geology, especially with F. Harold Weber, Jr., and James E. Kahle, who also mapped in this area and in the contiguous areas (this Bulletin).

FOOTHILL REGION BETWEEN LITTLE TUJUNGA CANYON AND PACOIMA WASH

Geologic Framework

Two major components dominate the structural framework of this area: the series of discontinuous, northward-dipping thrust faults of the Sierra Madre fault zone and the Merrick syncline (plate 2). The folding of the Tertiary and Quaternary sedimentary units into the partially overturned Merrick syncline provided the primary structural control for the current topography in the foothill region. The details of the formation of this syncline are not pertinent to the subject of this paper, but the coincidence of the axial trace of this fold to the trend of the thrust faults to the north implies a similar orientation of the stresses that produced both of these structures.

The thrust faults of the Sierra Madre fault zone include, from Little Tujunga Canyon to Pacoima Canyon: Little Tujunga fault, Lopez fault, and Buck Canyon fault. These structures separate pre-Tertiary rocks of the basement complex on the north from terrestrial sediments of the Saugus and Pacoima Formations on the south. Where exposed, the faults range in dip from 10° to 60° N. but generally dip less than 30°. In a few places (for example, on the west side of upper Kagel Canyon), south dips can be measured on fault planes at the contact between the Saugus Formation and the overlying rocks of the basement complex. These particular attitudes are best explained as resulting from large-scale landsliding in the vicinity of the fault trace. The upper Kagel Canyon locality has been interpreted as such (plate 2). Oakeshott (1958, p. 93) suggested that the anomalous reversed dip on the Buck Canyon fault at the head of Lopez Canyon could also be the result of such landslide effects.

As plate 2 shows, very large landslides are a characteristic feature of the basement terrain north of the Sierra Madre fault zone, as well as across the trace of the faults themselves. No evidence was found during the field work that would be helpful in determining the actual age of any of these large slides. Extending from the vicinity of the large composite landslides at the head of Marek Canyon are several stream canyons that are choked with great volumes of unsorted angular debris that evidently represent debris flow deposits. These large debris flows formed along the steep mountain front in basement rocks as additional manifestations of the conditions under which the large landslides formed. It may be that large landslides provided a supply of loose material saturated by rains during a prolonged wet period and that a large earthquake triggered the debris flows. Their spatial association with faults of the Sierra Madre system lends support to this hypothesis. The well-preserved aspect of the deposits, expressed as relatively level surfaces into which modern streams have made little headway, suggests youthfulness. However, as Howell (1949, p. 46) suggested, it may be that the deposits are so porous that streams have tended to cut their channels in the Saugus Formation where runoff is possible. If this is the reason for the unusual topography on and adjacent to these deposits, their youthfulness may be more apparent than real.

The San Fernando earthquake of February 9, 1971, dramatically revealed the presence of a previously unrecognized member of the Sierra Madre family of northward-dipping thrust faults—the San Fernando fault zone. Faults of this zone, however, rather than separating basement rocks from younger sedimentary rocks, transect the sedimentary units themselves. During the field investigations, the northern faults of the Sierra Madre fault zone (Little Tujunga fault, Lopez fault, Buck Canyon fault) were carefully inspected for features indicative of surficial movement during the earthquake, but no evidence was found. The surface effects that developed along the San Fernando fault zone to the south provide an abundance of features which are described and discussed below.

Tujunga Segment of the San Fernando Fault Zone

Surface expression. In the region between Little Tujunga Canyon and Pacoima Wash, the most spectacular and continuous surface effects of the earthquake lie along the Tujunga segment of the San Fernando fault zone. Surface breaks extend from the vicinity of the San Fernando Industrial Park eastward along Foothill Boulevard where, just east of Vaughn Street, the northeast sidewalk and curbing were lifted abruptly 85 cm (2.8 feet) relative to the pavement (90) (photo 1). The breaks continue across the

Photo 1. Frontal fault scarp of the Tujunga fault segment on Foothill Boulevard just west of the Foothill Nursing Home, which has since been razed (locality 90, plate 3). Note water in street from ruptured water mains. *Photo taken by F. Harold Weber, Jr., at 9:00 a.m., February 9, 1971.*

Photo 2. Low-altitude oblique aerial photo of the mouth of Lopez Canyon. Lettered localities: (A) scarp of the Tujunga fault segment; (B) rockfall caused by earthquake; (C) site of trench 8 in Blue Star Trailer Park; (D) bedding in Modelo Formation; (E) damage to flood control channel; (F) 38 cm (15-inch) left-lateral displacement of white line on Lopez Canyon Road. *Photo courtesy of the Los Angeles Department of Building and Safety.*

mouths of Lopez (photo 2), Kagel, and Little Tujunga Canyons and disappear near the mouth of Cassara Canyon. In some places (93, 118), the breaks of the Tujunga segment define a single continuous fault-line scarp, whereas in other places the segment consists of numerous interrupted, locally multiple (104) scarps and cracks that very closely approximate the change in slope at the base of the foothills. Asymmetrical compression ridges and mole tracks are the southernmost surface features of thrust faulting. Locally, abundant tensional cracks and high-angle fault scarps are common immediately north of the thrust fault scarps (94) (photo 3).

The scarps of the Tujunga segment attain their greatest height, 85 to 90 cm (2.8 to 3 feet), near the western end (90). In general, the scarps range between 40 cm (16 inches) and 50 cm (20 inches) high over their most continuous stretches. As is the case with the Oak Hill and Veterans faults, the best or sharpest scarps developed where artificially graded or leveled land surfaces were intersected by the faults.

The compressional aspect of the thrust fault scarps is readily observable at many places (118, 104). Direct measurement of the amount of shortening across the fault is only locally possible, however. The best place to measure shortening is where there has been displacement of linear man-made features. One such place where the shortening was measured is in the orange groves of Middle Ranch (118). The average shortening of two lines measured in the groves on the east side of Little Tujunga Wash is 1 m (3.3 feet). On the west side of the wash, measurement of the change in the spacing of the trees in three rows across the fault scarp averages 1.2 m (3.9 feet).

A noteworthy example of horizontal movement in the direction of the horizontal component of slip is provided by the offset of grooves in a road in the trailer park west of Lopez Canyon (T 8; also see map

Photo 3. View south and downslope of numerous tension cracks in white Modelo Formation siltstone above Tujunga fault segment scarp north of the end of Hoyt Street (locality 94, plate 3).

in plate 4). By coincidence, the road is oriented parallel with the horizontal component of slip. The grooves, which are nearly perpendicular to the road, were offset 159 cm (5.2 feet) when the road pavement moved northward relative to the trailer pad where portions of the grooves remain. That this measurement does not represent the exact amount of shortening is suggested by the measurement of the change in length of a steel pipe on the southeast side of the road (plate 4). This pipe was buckled and broken and appears to have been shortened 119 cm (3.9 feet) where the fault crosses it. This measurement is similar to that in the orange groves of Middle Ranch which implies that the maximum amount of shortening was similar toward both ends of the Tujunga fault segment.

The horizontal component of slip for faults along the Tujunga segment is predominantly left lateral (89, 92, 117), except near its eastern end in the vicinity of Little Tujunga Canyon (118). A detailed analysis of displacements and slip along the San Fernando fault zone is presented by Sharp (this Bulletin).

An attempt was made to measure the total amount of compression and tension expressed by the surface features north of the thrust in a small canyon N. 15° W. of the Pacoima Lutheran Hospital (105). From south to north across a gently south-sloping area beginning at the foot of the fault scarp, compressional features, similar to humps or waves, were measured over a distance of 30 m (99 feet) and include six scarps or scarplets totaling approximately a meter (3.28 feet) of shortening. Next, northward is an 18 m (59 foot) zone devoid of features and then a 33.8 m (111-foot) zone of 35 open cracks over which the extension represented by openings totals 44.6 cm (1.5 feet). Two possible explanations of the fact that the measured extension is less than half of the compression are: the remainder of the difference could be absorbed in the loose alluvium that underlies the entire zone or, alternatively, additional extension could have occurred on the faults upslope on the hills north of the frontal scarps (plate 3).

The low to moderate dip of the southernmost fault breaks along the Tujunga segment, ranging from about 10° to 50° N., can be observed where the trace of the fault crosses stream canyons (91, 95, 97). Immediately north of the compressional scarp (94, 105), high-angle, even vertical faults are locally common and probably represent tensional cracks near the lip of the thrust (photo 3). Accurate near-surface measurement of the attitude of the fault plane was made in several trenches (T3, T4, T8) (California Division of Mines and Geology, this Bulletin). Where details were revealed in trenches, the fault plane was found to coincide with the attitude of the bedding in the Modelo Formation (T3, T8). Very close to the surface, however, the fault plane flattens out (T8, plate 4) or even becomes slightly south-dipping (T4).

Geology. Could or should the Tujunga fault segment have been recognized by geologists before the earthquake dramatically demonstrated its presence? A brief review of earlier geological studies is given below to show that, although some geologists suspected or suggested the presence of a fault near here, no definitive, unambiguous evidence was discovered. Not having the benefit of hindsight, of course, their purposes were different from the present one. The following account of previous work provides a background for the discussion of those natural and artificial exposures that revealed the presence of the fault before the earthquake.

Useful geologic mapping of this area can be considered to have begun with the work of Kew (1924). His map (scale 1:62,500) differentiates the major rock units in the region but shows no fault along the base of the foothills. This fact was noted by Miller (1928), who placed a fault along the base of the foothills on his sketch map. Miller (1928, p. 210), after pointing out that evidence for the existence of a fault along the base of the foothills was not as good as that for other faults farther north, said, "but it scarcely seems probable that the straight, bold scarp, rising hundreds of feet for a distance of five miles, could have resulted wholly from erosion." Miller's larger scale map (1934, scale 1:84,000) also shows this suggested fault.

Mason Hill (1930) published the first detailed map of the region (scale 1:37,500) containing work done in 1928 with H. J. Buddenhagen. Hill did not show any fault that coincides with the Tujunga fault segment. Aware of the possibility of faulting south of the foothills, however, Hill placed a conjectural "Tujunga fault?" on his map several thousand feet south of the base of the hills. Insufficient evidence forced him to state (1930, p. 153) that "if a fault is present, the character of the displacement is unknown, but by analogy to the other structures [farther north] one reverse fault is tentatively shown" on his geologic cross section.

Oakeshott published several maps which include the area traversed by the Tujunga fault segment (1937, 1954, 1958), but he did not indicate any faults at the base of the foothills on any of them. White (1937), who carefully mapped (scale 1:24,000) the area between Little Tujunga Canyon and Pacoima Wash, discussed the evidence for a "possible Foothill fault" along the base of the hills. As earlier workers had, White (1937, p. 33) noticed the physiographic evidence for a "possible fault at or close to the break in slope" and observed that "this line cuts across the horizons in the Modelo to some extent, and is, therefore, not due to mere differential erosion." Circumstantial evidence, which White (1937, p. 33) believed implied faulting, includes his observation that Kagel and Little Tujunga Canyons "widen out to the north" which "suggests an upward movement to the south" as does the presence of multiple terrace levels within the foothills. The most positive evidence that White found remained, until the earthquake, the only direct observation of actual faults along what is now called the Tujunga fault segment. Just west of Lopez Canyon, White (1937, p. 33, plate 1) mapped "adobe-like terrace material . . . apparently faulted down on the south against Modelo."

Although White speculated on a "Foothill fault", his map shows only the small portion west of Lopez Canyon that was actually exposed. Credit is due to an undergraduate (George, 1937) writing his senior thesis on the geology of the area between Little Tujunga and Lopez Canyons for producing a map showing the closest approximation to the actual trace of the Tujunga fault segment. More willing to speculate than his predecessors (and successors as well, with the exception of Jahns and others, 1970) and with refreshing directness, he placed a "Foothill fault" on his map (scale 1:24,000) basing his decision (1937, p. 13) upon: the "remarkable straightness of the front of the foothill range" and the "relief of the relatively soft and easily eroded Modelo shales which make up the fore part of the foothills," which imply a fault scarp.

Larger scale mapping by Howell (1949, 1954, scale 1:12,000) of the entire area containing the Tujunga segment and by Merifield (1958, scale 1:12,000) of a portion of this area failed to turn up evidence for a fault here. Howell noticed the "remarkably straight" edge of the foothills north of Tujunga Valley (1949, p. 82) as earlier workers had. He stated, however (1949, p. 83), that "because of the lack of positive evidence for its existence, no fault has been indicated on the map or sections."

Detailed mapping of the geology along the Tujunga fault segment, mostly on vertical aerial photographs at a scale of 1:2400, has shown that natural exposures provide mostly indirect but, locally, very compelling evidence for both the existence and the youthfulness of faulting along the segment. Artificial exposures and subsurface information provide clear-cut evidence of faulting, had they been observed and analyzed before the earthquake. The above comment applies to the Tujunga segment and not to the Lakeview segment (Kahle, this Bulletin). It is likely that, if work had been done along the entire stretch between Big Tujunga Canyon and Pacoima Wash by one person prior to the earthquake, the evidence exposed along the Lakeview thrust would have lent heavy support toward assuming a conjectural fault along the base of the foothills where the Tujunga fault segment broke the surface.

As discussed above, White (1937) discovered some of the best evidence for faulting along the hill-

Photo 4. View eastward along the western part of the Tujunga fault segment about 213 m (700 feet) northeast of Foothill Boulevard. Scarp (A) of the Tujunga fault segment, which separates north-dipping siltstone and sandstone of the Miocene Modelo Formation (B) from dark reddish-brown colluvial debris and alluvium (C), which has been dissected and is above the level of the modern alluvium (D). Close inspection of the attitude of the contact in this vicinity would have revealed before the earthquake that the Modelo Formation does indeed rest upon alluvium. *Photo taken by F. Harold Weber, Jr.*

slopes west of Lopez Canyon (photo 4). Exposed above the level of the modern alluvium are remnants of a distinctive, mappable deposit of poorly sorted, weathered, older colluvium and alluvium possibly of debris flow origin. Both White (1937) and Howell (1949) mapped this unit, but only White placed a fault between it and the Modelo sandstone to the north. In addition to the easily recognizable character of this material, an abrupt change in the bearing of the gullies that dissect the slopes from S. 20° E. in the steeper Modelo sediments to S. 35°–45° W. in the older alluvium at the contact of the two hints at the change in geological conditions. An accurate plot of the trend of the contact across the topography between the Modelo Formation and the older alluvium at one locality in particular (photo 4) demonstrates that the Modelo sediments must indeed overlie the alluvium.

The presence of terrace deposits, which were discussed in detail by White (1937, p. 18–20) and by Howell (1949, p. 44–48), at various levels within the foothill region in general and along the frontal slope in particular (plate 2) indicates uplift and implies repeated faulting to accomplish it. The distinctive red-weathering unit which has been mapped as older colluvial deposits beneath the Tujunga segment (plate 2) was mapped by White (1937, plate 1) as an "adobe conglomerate," which he suggested may be a residual topsoil. Unfortunately, no information on the actual ages of the terrace deposits or older colluvial debris is yet available that could make it possible to estimate rates of uplift. Gullying of an old bulldozer cut in some of the lower elevation (that is, youngest) terrace deposits exposed white Modelo sandstone overlying unconsolidated coarse bouldery terrace deposits at one place (103) which is approximately 45 m (150 feet) north of the southernmost fault scarp formed during the earthquake. This may indicate the presence of an imbricate, older fault north of the Tujunga fault zone.

Undoubtedly, the best artificial exposure of the Tujunga fault along the entire segment was created during construction of the Blue Star Trailer Park west of Lopez Canyon. Perhaps it escaped the notice of geologists because it may not have remained open very long before being covered by a wall of masonry. The fault zone is openly displayed there once again because the wall, which was broken at the time of the earthquake, has been removed (map in plate 4).

A few feet west of this cut, the California Division of Mines and Geology excavated a 17.7 m (58 foot) trench across the 70 cm (2.3 foot) high earthquake scarp to expose the geology (T8: California Division of Mines and Geology, this Bulletin, photo 5). This trench exposed a section similar to the artificial exposure in the Blue Star Trailer Park. A detailed sketch of the western wall of the trench and a locality map of the area are given in the pocket (plate 4). It was possible to investigate the geology in great detail because the moist, weakly to moderately cemented units were easily cleaned and trimmed on the walls of the trench.

Photo 5. Deformed asphalt pavement and uptilted concrete slab along the 70 cm (2.3-foot) high scarp of the Tujunga fault segment in the Blue Star Trailer Park. Trench 8 (plate 4) was cut near shovel. Note also rockfall debris triggered by earthquake above scarp. *Photo by James E. Kahle.*

The fault scarp was formed in an area of asphalt paving that covers a graded bedrock surface on sedimentary rocks of the Modelo Formation. The straightforward geology in the vicinity of the scarp, revealed by the trenching, consists of two fault planes or planar zones. The northernmost of these faults parallels the strike (N. 80° W.) and dip (32° N.) of the Modelo sandstone and siltstone layers as a zone of moist brown clayey, gougelike material. Slickensides, which plunge 22° in a N. 50° E. direction, were found on the upper surface of this material.

Most of the displacement apparently took place along the northern fault plane. The southern fault plane is expressed as a thinner zone of loose material, and it was not possible to tell how much displacement occurred along it. The change in dip of the fault near the surface is a result of the "falling over" of the unsupported upper sedimentary layers above the fault.

The trench revealed that the faulting in this earthquake took place within the Modelo Formation rather than between Modelo strata and alluvium as was seen to be the case at several other places along the Tujunga segment (T3, T4; also see discussion by Kahle of relations along the Lakeview segment, this Bulletin). Faulting of this type is most likely not a unique feature here but probably has occurred elsewhere (106) along the segment. The reason for faulting of this type, as well as for the development of a well-defined scarp here, may be related to the fact that the bedrock surface had been graded before the earthquake. In general, well-defined scarps elsewhere are restricted to such graded surfaces where loose alluvium or soil had been removed. This aspect of scarp development is especially well exemplified by the Oak Hill (T1) and Veterans faults (47). It is possible that the faults exposed in trench 8 formed where they did with respect to the Modelo/alluvium contact because the toe of the original hillslope, which was located probably about 1.5 m (5 feet) north of the southern end of the trench, had been cut away during grading operations and the faulting took a more direct route to the surface.

A record of previous faulting on the Tujunga fault is dramatically displayed in the section exposed in trench 8 (plate 4). The complexity of the deformation in the generally soft, thinly bedded Modelo sediments in the central part of the trench attests to repeated fault movements. The axial traces of several of the folds shown in the sketch plunge from 4° to 8° in a N. 55°–60° W. direction reflecting the lateral as well as the horizontal components of earlier movements on this fault zone. Further record of repeated earlier movements is given in the relation of the deformed Modelo Formation and the underlying older alluvial debris. A cross trench (plate 4) was dug near the scarp where, at a depth of more than 4 m (13 feet), the contact between Modelo sandstone and alluvial material was encountered. The Modelo Formation has overridden the alluvial material for at least 13.1 m (43 feet). The displacement on this fault is probably much greater as suggested by the uniformity of its dip, projecting the evidence in the cross trench to the section of trench 8. By analogy with discoveries along the Lakeview segment (Kahle, this Bulletin), the total displacement along the Tujunga fault segment may approach hundreds of feet. Unfortunately no datable materal was found in the alluvium of trench 8; therefore, the pre-earthquake faulting can only be termed youthful.

At the southern end of trench 8, the decurved aspect of the near-surface portion of the pre-earthquake fault separating underlying alluvium from debris of the Modelo Formation and older slope wash deposits from the hill which extended this far south before grading is very similar to the shape of the earthquake fault plane exposed in trench 4 (T4) west of trench 8 (T8) at the base of a natural slope. Trench 4 was dug across a 60 cm (2-foot) high scarp in soil and exposed the near-surface aspect of the fault plane that separates debris of the Modelo Formation containing shale chips, pebbles, and cobbles on the north from older alluvium which is poorly bedded. The fault plane dips north 15° near the northern end of the trench, bends over near the surface, and dips shallowly southward, all in a distance of 1.8 to 2.4 m (6 to 8 feet), identical to the pre-earthquake fault in trench 8. The pre-earthquake fault exposed in trench 8 did not move during the 1971 event, but it separates possible slope wash deposits from older alluvium. This relationship suggests very young faulting because of the easily eroded nature of the deposits above the decurved portion of the fault. Bonilla (1972; in press) has suggested that surface faulting may have occurred on an older fault at the Oak Hill fault (T1), north of trench 8 about 915 m (3000 feet), about 200 years ago. A wood sample he found in collapse-rubble (?) just below the buried old fault scarp in a trench was dated by the radiocarbon method as being less than 200 years old. It is also possible but, unfortunately, not as neatly indicated, that faulting this recent took place in the vicinity of trench 8 and, by implication, along the whole Tujunga segment.

Movement on the Oak Hill fault and the Tujunga fault segment took place during the 1971 earthquake because the stresses being released were of the appropriate orientation to involve both of these structures. Therefore, it is not unlikely that, if the older buried fault scarp 1.2 m (4 feet) north of the Oak Hill fault moved about 200 years ago as suggested by Bonilla (1972; in press), the forces responsible for such movement similarly affected the Tujunga segment.

A much simpler geological picture was revealed in a trench (T3) dug north of Carl Street than in the other previously discussed trenches. The trench was cut across a low 7.6 cm (3-inch) high compression ridge exposing a well-defined single fault plane that strikes east-west and dips 44° N. parallel with the bedding of the Modelo Formation. The fault juxtaposes shale and siltstone on the north against poorly sorted conglomerate with a coarse sandy matrix which may represent an alluvial fan or debris flow deposit.

Surface Faulting North of the Tujunga Segment

Oak Hill fault. Surface faulting along the western end of the Lakeview thrust (Kahle, this Bulletin) crossing Little Tujunga and Kagel Canyons, about 366 m (1200 feet) north of the Tujunga segment, produced a scarp which is almost identical to the Tujunga fault segment scarp across Little Tujunga Canyon.

Faults other than thrusts were also active during the earthquake at places away from the major zones of thrusting. A type of fault in which the dip and strike of the fault parallel the dip and strike of the enclosing strata is known as a bedding-plane fault. Such a fault is the north-dipping Oak Hill fault (T1) (Kamb and others, 1971, p. 51) in Lopez Canyon (T1, photo 6) where a very prominent, partly overhanging 80 cm (32-inch) high scarp formed. A detailed study of the effects in the vicinity of the Oak Hill fault, reported by the U.S. Geological Survey (1971, p. 67–69), showed that this fault also had a left-lateral component of slip averaging 80 cm (32 inches).

A sharply defined scarp developed only over a graded bedrock surface for a length of 45 m (150 feet) although surface breakage could be traced for almost 245 m (800 feet) along this fault. A trench about 23 m (75 feet) east of the well-defined scarp was cut in unconsolidated alluvium and fill across a mole track or surface hump of the Oak Hill fault. Even though the ground at the surface was cracked and warped, no evidence of faulting was seen in the walls of the trench. Evidently movement in the loose material is distributed in such a way that it escapes detection in cross section. A lack of planar marker layers (for example, beds), which would attest to offset, is a primary reason for failure to observe the faulting. Elsewhere, in several trenches across scarps of the Tujunga segment in a field east of the mouth of Lopez Canyon, evidence for faulting was lacking where the trenches dissected only unconsolidated soil, slope wash debris, or alluvium. It can be concluded from these observations that trenches in unconsolidated, massive or unstratified materials may be of little or no value when it comes to determining whether or not faulting has occurred.

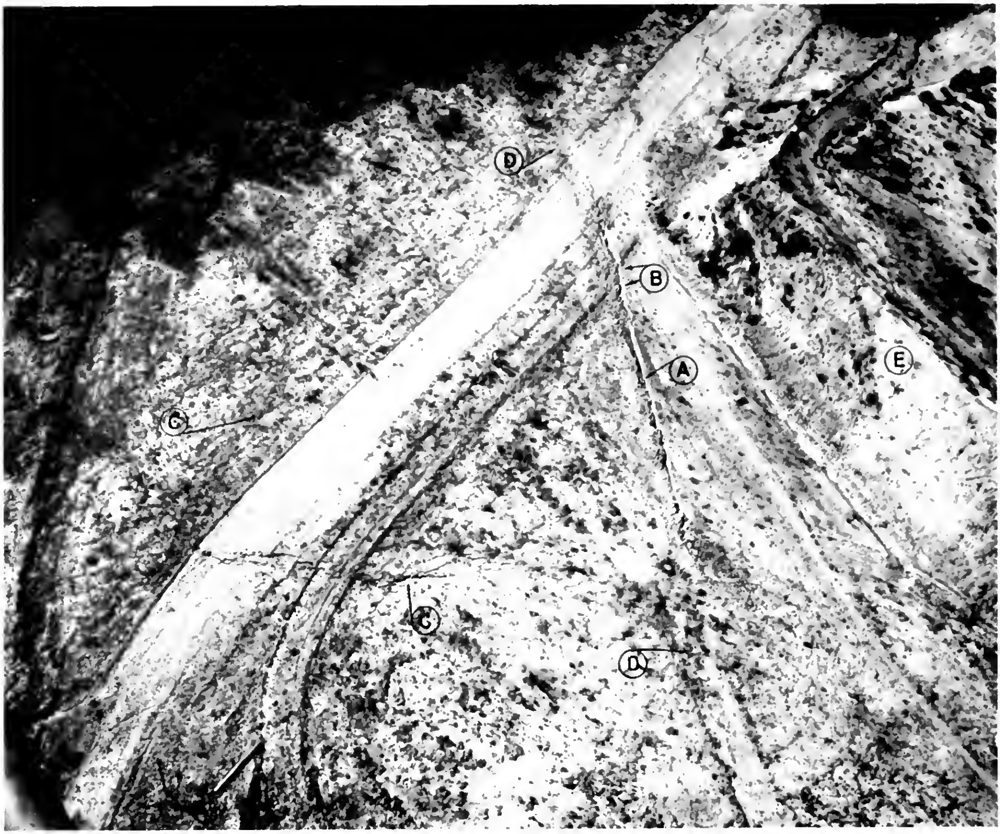


Photo 6. Low-altitude aerial photo of the Oak Hill fault scarp in Lopez Canyon. Lettered localities: (A) 80 cm (32-inch) high scarp in bedrock striking N. 75° W., dipping 62° N; (B) dirt ridge offset left laterally about 85 cm (33 inches); (C) settling cracks possibly delineating the contact between bedrock at shallow depth and deeper fill and alluvium; (D) mole track or hump where faulting occurred in loose fill and alluvium; (E) sandstone, siltstone, and conglomerate beds of the Towsley/Pico Formation whose attitude is similar but not identical to that of the fault. *Photo courtesy of the Los Angeles Department of Building and Safety.*

The north side of the Oak Hill fault moved up in north-dipping strata. Elsewhere, on other bedding-plane faults (98,100), the north side moved down in north-dipping strata by amounts equal to or greater than south-side down faults (photo 7). Faults that transect bedding, the most important of which is the Kagel fault discussed below, were also active during the earthquake (111; 101).

Kagel fault. The Kagel fault, originally mapped and named by Hill (1930), strikes N. 75° E. across the strike of the bedding in both the Modelo and Towsley/Pico Formations, as well as across the contact between them (plate 2). During the earthquake, the Kagel fault may have been active over its entire length; but surface breaks are not continuous along its trend. The dip of the fault varies along the strike. Although Hill reported a 75° N. dip in a canyon bottom about 610 m (2000 feet) east of Dexter Park, the exposure from which he determined this dip could not be found. The fault is exposed, however, in a roadcut on the ridge east of Dexter Park. At this locality, the fault, which dips almost vertically, is expressed as a zone of gouge separating coarse conglomerate on the south from deformed gray sandstone on the north.

White (1937), George (1937), and Howell (1949) all considered the Kagel fault to be a reverse fault which dips about 60°s in the vicinity of Kagel Canyon. Hill (1930, p. 152) stated simply, without elaboration, that drag effects along the fault suggested a left-lateral component to displacement along the Kagel fault. George (1937, p. 15) also considered that a lateral component to the faulting was likely. White (1937, p. 29) and Howell (1949, p. 83), on the other hand, considered the Kagel fault to be simply a reverse fault. All of these workers mapped the well-exposed folds in Kagel Canyon which are spatially related to the Kagel fault (plate 2), as did Merifield

Photo 7. North-dipping bedding-plane fault in sandstones of Towsley/Pico Formation on ridge east of Indian Canyon (locality 98, plate 3). Scarp is 1 m (3.2 feet) high. This scarp is stratigraphically very close to the contact with the overlying Saugus Formation. Note shattered ground in background.

(1958), who argued that these folds in the Modelo Formation implied strike-slip movement along the Kagel fault. He reasoned (1958, p. 44) that, if the Kagel fault is "assumed to be a reverse fault (that is, a fault resulting from compression), the movement would be opposed to that of the other faults in the area, in which north has exclusively moved up. If on the other hand it is a normal fault, it is difficult to explain the compression folds almost certainly related to the faulting. Consequently, left-lateral strike-slip movement best explains the observed relations." He estimated a total horizontal separation of about 1067 m (3500 feet) of the base of the Towsley/Pico Formation along the Kagel fault.

If the features resulting from movements along the Kagel fault during the earthquake are indicative of previous faulting, the earthquake provided support for the position that the Kagel fault has both normal and left-lateral components of movement. Most of the scarps formed during the earthquake are up on the north. The greatest vertical offset was 85 cm (2.8 feet) (102). Most of these scarps are vertical and probably do not reflect the true dip of the fault. That the fault is south dipping is indicated by the slightly irregular trace where it crosses topography, as shown on the geologic map. Just east of the bottom of Bartholomaus Canyon (107), the actual fault plane was exposed as a result of the earthquake. The Kagel fault dips 46° S. and here separates sheared and fractured conglomerate of the Towsley/Pico Formation from gray gypsiferous, highly contorted shale and siltstone of the Modelo Formation. Movement here was up on the south rather than down as is much more common for the Kagel fault surface breaks. However, 60 m (200 feet) upslope (eastward) and also at the top of the ridge, scarps developed which are down on the south. The explanation for this change in the facing direction of the scarps may lie in a consideration of the lateral component of faulting. In the bottom of Kagel Canyon, the total offset on the Kagel fault was 25 cm (10 inches) left lateral as measured in the road.

The surface breaks map (plate 3) shows that the highest scarps formed at the tops of ridges (102) and on west-facing slopes. Curiously, east-facing slopes (Bartholomaus Canyon and Kagel Canyon, for example) lack even minor evidence of surface breakage. The western side of Kagel Canyon is also the site of large landslides in the Modelo shale and siltstone, which moved, in part, during the earthquake, destroying several houses.

Spatially related to movements along the Kagel fault are surface effects not on the trace of the fault but probably related to movements at depth along it. Such a feature is a large, reactivated landslide on the east side of Bartholomaus Canyon (photo 8). As the geologic map shows, this landslide is one of three slides on the east side of Bartholomaus Canyon that was reactivated by the earthquake. A large slide on the west side of the canyon did not move during the earthquake. The relation of the slides to the folds in the Modelo Formation suggests that perhaps minor movements on these folds may have occurred. Surface effects in Kagel Canyon may also be related to this phenomenon.

Currently available exposures of the Kagel fault indicate that it dies out in the bedding of a soft gray silty sandstone unit of the Towsley/Pico Formation about 457 m (1500 feet) east of Dexter Park. Furthermore, the lack of deformation in the sedimentary layers east of there, similar to that encountered in Kagel Canyon, supports the concept of diminishing movement on the Kagel fault and dispersal into bedding-planes. The development of excellent scarps (photo 9) at localities 115, 114 is somewhat puzzling because these scarps do not appear to coincide with the trace of the Kagel fault. At one locality (115), the scarp is about 90 m (300 feet) north of the Kagel fault, which is exposed in a roadcut on this ridge. This particular scarp formed very close to the topographically highest point on this ridge and parallels the strike of the bedding in the Towsley/Pico sediments but dips 70° to 80° S., whereas the beds dip 50° N. This particular scarp may represent a new fault formed near the end of the Kagel fault in response to the movements during this earthquake. East of this locality (114), the north-facing scarp, which also is situated at the very top of a small peak, may have resulted from focusing of shaking energy attested to by the shattered ground hereabouts and the rockfalls and slope failures in this vicinity and may not actually be a "fault" scarp. This intense shaking also appears to have caused the heavy damage to new U.S. Forest Service facilities in lower Marek Canyon. No evidence was found that would indicate that the Kagel fault extends that far east. The surface cracks in the roads of the facility all appear to be related to the compaction of fills at the contact with cuts or edge breakage due to bank failures in the terrace material thereabouts.

Along the western end of the Kagel fault, scarps similar to the one at locality 115 formed north of the actual fault trace. These scarps also had the largest

Photo 8. Large reactivated landslide on the eastern side of Bartholomous Canyon. Breakaway scarp is approximately 60 m (200 feet) across. Surface breaks along the Kagel fault trend upslope at the base of the rockfalls in the upper left corner of photo. *Photo courtesy of the Los Angeles Department of Building and Safety.*

offset at the tops of ridges and diminish in height downslope in both directions until they disappear. Farther west, surface faulting spatially related and probably associated with movement on the nearby Kagel fault formed scarps up to 130 cm (4.3 feet) high at the base of massive conglomeratic beds in the Towsley/Pico Formation.

Surface Effects Other Than Faulting

Landslides. Various kinds of earthquake effects in addition to surface faulting are widespread and abundant in the area north of the Tujunga segment (plate 3). Perhaps the most widespread surface features are the slope failures triggered by the earthquake or, in some cases, by aftershocks. Although Morton discusses these effects elsewhere in this Bulletin, it is appropriate to mention them here to emphasize their obvious or apparent relation to the underlying geology.

A comparison of the surface breaks map (plate 3) with the geologic map (plate 2) demonstrates the lithologic control over the formation of landslides as Morton has pointed out (1971a; 1971b; this Bulletin). In the area north of the Tujunga segment and south of the basement rocks, most larger landslides occurred in rocks of the Modelo Formation and Towsley/Pico Formations with relatively few forming in the region underlain by the Saugus Formation. Within the Saugus Formation, many of the larger slides are failures of the steep banks of terrace or fan deposits resting on tilted Saugus beds and not failures of the Saugus rocks themselves. Conversely, minor soil failures, cracking, and falling away of the sharp edges of ridges underlain by Saugus rocks appear to be more common than in the areas underlain by the older Tertiary rocks. The varied lithology, as well as the steeper topography developed on it, helps to explain the abundance of slope failures in the terrain underlain by the older

Photo 9. Fault scarp across top of ridge east of Dexter Park (locality 115, plate 3). Vertical displacement along the scarp ranges from 25 to 76 cm (9.8 to 30 inches) up on the north. No evidence of lateral displacement. Scarp is 90 m (300 feet) north of the trace of the Kagel fault. Pencil for scale on scarp in lower left of photo.

Photo 10. Earthquake-caused damage to a minor road on the east side of Indian Canyon 490 m (1600 feet) northeast of Oak Hill School. The landslide and rockfalls are both related to the failure of dip slopes in Towsley/Pico sandstone and conglomerate beds. Bedding planes are visible in the upper left portion of the photo.

Photo. 11. Large rockfall in Pacoima Canyon gorge south of Pacoima Dam that did not fall until several hours after the main shock.

Tertiary sediments (photo 10). An additional cause may be the proximity of these units to the zone of surface faulting and the probable greater ground motion to which they were subjected.

The reactivation of large landslides in Bartholomaus Canyon (photo 8) has already been mentioned under the discussion of the Kagel fault. A causal relationship to movements on the Kagel fault was inferred there. The large rockfalls directly along the Kagel fault resulted, not only because of severe ground movements, but because faulting in the past has juxtaposed resistant, coarse conglomerate against weak siltstone and shale and cliffs naturally formed along their contact.

As the surface effects map (plate 3) shows, numerous large rockfalls formed in the vicinity of Pacoima Dam and in the rugged gorge of Pacoima Canyon. One of the largest of these rockfalls (photo 11) did not form during the major shock but fell several hours later as is proved by its absence in photo 12. This is an illustration of a geologic hazard created directly by an earthquake. It remains an unknown threat of danger not yet past until recognized or, of course, until it falls.

Several very large landslides of unknown age are shown on the geologic map in the area underlain by basement rocks. Only one of these slides (upper Kagel Canyon above the trace of the Lopez fault) was partially "reactivated" by the earthquake in the same manner that landslides in the sedimentary rocks to the south were. The large composite slides that conceal the trace of the Little Tujunga fault in upper Marek Canyon exhibited a distinctive kind of response to the earthquake. These slides contain large blocks of granodiorite and other basement rock types ranging up to tens of feet on a side. Because the slide did not move as a body during the earthquake, it is assumed that the earthquake waves moved through the slide rather than affecting it as a unit relative to the bedrock beneath it. Large, previously fractured blocks within the slides, however, became disjointed and some of them cracked and fell apart.

Small landslides and debris falls formed in Maple Canyon along the toe of a huge landslide north of Kagel Mountain, but there is no evidence that this slide moved downslope as a unit. The scarps that formed along the top of Kagel Mountain (49) can be followed discontinuously for thousands of feet (plate 3). They appear to offset bedrock, locally, and are down on the upslope side in certain places. They may be related in some way to movement of what may be a large landslide on the north slope of Kagel Mountain.

Settlement of fill. Differential settling or compaction of artificial fill due to shaking resulted in the formation of surface cracks and non-tectonic scarps at the contact of the fill with natural ground. This phenomenon was locally responsible for considerable damage, particularly to roads and other paved areas. Cracking around the boundaries of a large sanitary landfill (plate 3) on the hilltop west of the mouth of Lopez Canyon is a prime example of surface breakage of this type. Settling of fills in the vicinity of Camp

Photo 12. Oblique aerial photograph of Pacoima Dam and the Pacoima Canyon gorge taken about 11:00 a.m. on February 9, 1971. Dust can be seen rising from continuing rockfalls to the right (east) of the dam. Locality A is site of large rockfall shown in photo 11 that did not fall during major shock.

Karl Holton and the U.S. Forest Service facility in Marek Canyon resulted in disruption of pavements and other damage. The scarp trending southwest across the lawn in Sholom Memorial Park in Kagel Canyon coincides with the contact of an artificially filled stream channel and the natural older alluvium.

Shattered ridge tops. Another distinctive category of non-faulting surface effects is the remarkable and, locally, spectacular development of shattered ridge tops. The distribution of these features is plotted in plate 3. In general, this effect is expressed as chaotic disruption of soil where it is commonly less than 60 cm (2 feet) thick along ridge crests and peaks underlain by sandstone and conglomerate strata. The shattering may be localized along certain strata (99, 110, 113; photos 7 and 13), or it may be concentrated where there is especially angular topography (109, 112). An example of the association with particular layers is shown in photo 13 (110). In this case, a sandy cobble conglomerate layer of the Saugus Formation exhibited shattering at ridge tops for 550 m (1800 feet) along the strike of the bedding. The induration and lithology of this bed is not noticeably different from that of undisturbed beds above and below it in the Saugus Formation. An explanation for localization here is suggested by the presence of minor surface faults which bracket the bed at the eastern end of the shattered portion and beyond the western end (plate 3). The shattering of the soil along this layer may represent a dispersal at the surface of energy that was concentrated here along bedding planes. In addition, the rocks are not as well lithified here as they are where bedding-plane faults did develop (98, for example).

Photo 13. Intensively shattered apex of ridge in the Saugus Formation west of Marek Canyon (locality 110, plate 3). Note outwardly tilted blocks of soil 15 to 20 cm (6 to 8 inches) thick on right side of photo.

Shattering was well developed in areas of badland topography (109) and in areas characterized by the presence of numerous sharp peaks and ridge crests that are typical of terrain underlain by the Saugus Formation (112). Within areas subjected to the same intensity of shaking, only the tops of narrow ridges were shattered. This suggests that the cohesiveness of the soil was overcome at these localities by magnification of the energy relative to the surface area due to the focusing effect of converging planes or surfaces. Less well-indurated materials lying on more consolidated rocks also were shattered in less angular but topographically high places (photo 14). The shattering of terrace deposits on Sugarloaf (108) is an example of this type.

Photo 14. Shattered ridge top on the eastern end of Sugarloaf (locality 108, plate 3) west of Kagel Canyon. Material disrupted here is an old terrace deposit that caps this peak in the Saugus Formation. Note the jumbled blocks of sod, some of which are upside down. *Photo by James E. Kahle.*

An additional observation concerning the localization and lithologic control of shattered ridge tops can be made by comparing plates 2 and 3. Of special interest is the restriction of shattered ridge tops to rocks of the Towsley/Pico Formation in the vicinity of the contact with the overlying Saugus Formation. This particular feature is best seen east and west of Kagel Canyon. The localization of shattered ridges in rocks near this contact is noteworthy here. Strong ground effects, of which shattered ridges are an indication, were also demonstrated by the damage to Los Angeles County Fire Station No. 74 in the Dexter Park area of Kagel Canyon.

The evidence for unusually high acceleration in the vicinity of the fire station was discussed by Morrill (1971), who also presented several pictures of the exceptionally strong effects. In this vicinity, bedding-plane faults in the Towsley/Pico rocks with left-lateral displacement of 5–10 cm (2–4 inches) were common across Kagel Canyon Road (plate 3). Water tanks on the ridge east of Dexter Park were moved and connections to pipes broken. Water tanks west of Kagel Canyon also moved off their foundations, buckling the steel plates near their bases and breaking the connections with pipes. Within Dexter Park itself, the road and the stone wall along the east side of the park was cracked almost exactly at the contact of the Towsley/Pico and Saugus Formations and not noticeably affected elsewhere. Cracking of the road entering the park on the west side past the County fire station was restricted to that portion overlying Towsley/Pico rocks. Minor damage to this road developed only locally over Saugus rocks. Farther to the east along the contact, strong shattering, abundant rockfalls, and damage to man-made structures such as the U.S. Forest Service facility in Marek Canyon were concentrared along but not restricted to rocks of the Towsley/Pico Formation as they were in Kagel Canyon. As suggested under the discussion of the Kagel fault, very strong shaking within the Saugus Formation at the Foresr Service facility may have been related in some way to the amplification of ground movement beyond the end of surface faulting along the Kagel fault.

The abundant surface effects and damage resulting from higher acceleration along the contact between the Saugus and underlying rocks must be related to the differences in the underlying geology. The better cemented, better sorted Towsley/Pico rocks evidently responded differently to the passage of earthquake energy than the Saugus rocks, which are less well consolidated and lithologically more varied. Perhaps the Saugus sediments are capable of dispersing energy better. What took place along the contact during the San Fernando earthquake implies that the gross lithological differences, as well as the physical properties of the rocks themselves, should certainly be taken into account when studies are made of sites for critical facilities.

Post-earthquake surveying data provided additional support for the correlation of earthquake effects and the contact between the Towsley/Pico and Saugus Formations. In their preliminary survey, Burford and others (1971, p. 81) reporred that the largest vertical displacements they documented were on the loop through Kagel and Lopez Canyons. The largest change in elevation, 2.281 m (7.48 feet) (Burford and others, 1971, figure 1), lies almost precisely on the formational contact in Lopez Canyon. Further data support the preliminary observations. Savage (1971, figure 5) presented a map in which the greatest changes in elevation (at least 2 m) were contained within an elongated closed contour bounding the area of permanenr uplift that extends from Little Tujunga to Pacoima Canyon. The axis of this area of highest permanent deformation coincides very closely with the formational contact discussed above. West of Pacoima Canyon, the trend of the greatest elevation changes also appears to correspond closely with the contact (see discussion of this area by Weber, this Bulletin).

The concentration of effects and magnitude of permanent surface deformation at the formational contact may be related to the gross geologic structure, as well as to the difference in lithology between the rocks. Savage (1971, p. 112) has suggested that the earthquake "faulting appears to be in response to a north-south compressive force which acts upon the whole region." No doubt forces of similar orientation in the past were responsible for the development of the very large overturned fold that is the Merrick syncline as well as the north-dipping thrust faults. It is extremely difficult to prove that actual folding did occur in this structure during the earthquake. Minor surface effects in the center of the Merrick syncline were locally strong (for example, in Limekiln Canyon and near Little Tujunga Canyon). Weber (this Bulletin) discusses circumstantial evidence suggesting folding(?) in the Juvenile Hall area.

PACOIMA CANYON TO WILSON CANYON

With the exception of surface faulting on the Veterans fault, numerous slope failures, and, locally, shattered ridges—the effects of the San Fernando earthquake on the surficial geology of this area are rather slight compared to the damage to man-made structures. Because there will continue to be questions as to why this area experienced such severe ground motion without producing major geological surface effects, an account of the geologic framework is given below. This is followed by a discussion of effects which were produced. The geology was mapped on post-earthquake aerial photos at a scale of 1 inch equals 200 feet (1:2400). Almost every ridge top and stream bottom was traversed as were all the roads in the area.

Geologic Framework

The geology along the front of the San Gabriel Mountains in this vicinity consists of the pre-Tertiary granitic and metamorphic rocks of the basement complex with Pleistocene and younger terrestrial sedimentary rocks either deposited upon or faulted against them (plate 2). This discussion concerns the geology of the foothill belt which is 450 to 900 m (1500 to 3000 feet) wide and lies between the alluvial cover of the northeastern Sylmar plain on the south and the basement complex on the north. Within this narrow belt, rocks of the lower Pleistocene portion of the Saugus Formation, middle Pleistocene Pacoima Formation, upper Pleistocene terrace and alluvial fan deposits, and Holocene alluvium are exposed.

Structurally, folding is the dominant feature but faulting is locally significant. A detailed discussion of the geology of the Saugus and Pacoima Formations is given below, so that an assessment of the significance of the faulting can be made.

Exposures of Saugus Formation are limited to small areas east of the Veterans Administration Hospital site and near the mouth of May Canyon. Oakeshott (1958, p. 84) has ably summarized the lithology of the Saugus Formation which consists of "light-colored, poorly sorted, loosely consolidated conglomerate and coarse sandstone, commonly crossbedded, which were deposited as fluvatile and alluvial-fan sediments around the western end of the San Gabriel Mountains." Saugus conglomerate in this area contains numerous boulders and cobbles of anorthosite and related rocks, as well as the more abundant granitic rock types. Saugus beds dip uniformly to the northeast or northwest and presumably form a continuous section of northward-dipping rocks, concealed by alluvium, extending beneath the Sylmar plain from the foothill belt southward, approximately 3.2 km (2 miles), to the contact with the Towsley/Pico Formation (plate 2).

The middle Pleistocene Pacoima Formation was named by Oakeshott (1952), who designated as the type locality exposures near the mouth of Pacoima Canyon about a half mile south of Pacoima Dam. Oakeshott (1958, p. 86) described the Pacoima Formation as a fanglomerate or sedimentary breccia which "is very poorly sorted, consisting of sharply angular pebbles and boulders of a wide size range all deposited together with a dark brown or reddish-brown mudstone-soil matrix." All the clasts in the Pacoima are locally derived, except, of course, those that are reworked from the Towsley Formation west of Wilson Canyon. Rock types can be recognized in the deposits that are identical to those cropping out just upslope in the basement complex.

The Pacoima Formation is readily distinguished from the Saugus Formation because it has much poorer bedding, poorer sorting, and much more angular clasts of local derivation; it lacks the distinctive anorthosite and other distantly derived rocks found in the Saugus; and it is commonly dark brown or red in contrast to the light gray or white of the Saugus sediments. The contact between the Saugus and Pacoima Formations is exposed in lower Loop Canyon, where there is a 20° to 40° depositional angular discordance, east of the mouth of May Canyon where the formations are almost conformable, and west of May Canyon, where there is 10° to 20° of discordance.

The contact between the Pacoima Formation and the basement rock is a variable one. Northeast of the Veterans Administration Hospital, the basement rocks have been thrust over the Pacoima. Just east of Loop Canyon, the Pacoima is in depositional contact on the basement. West of Loop Canyon, the contact is a south-dipping normal fault that can be traced as far as the canyon north of the May Canyon debris dam. The remainder of the contact to the west is a depositional one.

These conclusions are in contrast to those of Oakeshott (1958), who showed the contact east of Loop Canyon between Pacoima and basement rocks to be a depositional one. Between Loop Canyon and Wilson Canyon, Oakeshott (1958, p. 86) stated that "the basement crystalline rocks have been thrust southward over the Pacoima Formation at angles varying from 45° to 60°, cutting out the north limb of the Little Tujunga [Merrick] syncline." The "thrust" to which Oakeshott referred was defined by him (1958, p. 93) as the Hospital fault. He considered the type locality of the fault to be 0.5 km (0.3 mile) north of the Veterans Administration Hospital evidently in an exposure on the May Canyon truck trail on the west side of Loop Canyon where he showed it dipping 60° north.

Although Merifield (1958) depicted a "Hospital fault" on his map, he showed it differently from Oakeshott. Merifield (1958, p. 37) said that "a dip of 60° north was obtained on the [Hospital] fault in an exposure on the ridge east of Loop Canyon; furthermore, the straight character of the fault [across the topography] suggests the dip is nowhere much less than this figure." Merifield differed in locating this "fault", as well as in its attitude. His map shows it trending northwest away from the Pacoima-basement contact about halfway between May and Wilson Canyons.

The detailed mapping during the present study, some excellent new exposures, and an emphasis on the geology specifically along this contact have resulted in a geologic map considerably different from that of earlier workers. The particular evidence available from east to west along this contact is discussed below in detail so that the factors can be assessed from which the present conclusions were drawn. Finally, implications of these conclusions with respect to the earthquake are discussed.

Between Pacoima Canyon and Loop Canyon, exploration pits and bulldozed roads have made new exposures on the lower slopes along the mountain front. One of these roads exposes the thrust-faulted contact between slightly foliated granodiorite on the north and Pacoima Formation on the south. The dip of the fault is 20° to the north and the Pacoima Formation dips 32° N. directly beneath the fault. A few feet west of this roadcut, there is a natural exposure of granodioritic rocks overlying reddish Pacoima Formation in a steep-walled gully. The mapped fault trace closely follows the contours, confirming the shallowness of dip as measured in the roadcut. Moving westward to the ridge just east of Loop Canyon, the contact between Pacoima and basement rocks dips moderately toward the south as is shown by the intersection of the contact with the topography. Furthermore, this contact is a depositional one as is reflected in the similarity between the dip of the contact and the dip of the bedding in the Pacoima Formation. The map shows that the Pacoima beds are folded into a gentle syncline. The beds near the basement dip away from the contact rather than toward it as is the case to the east, discussed above, where the basement is thrust over the sediments.

An analogy can be drawn to the thrust fault east of Pacoima Canyon where basement rocks overlie Saugus Formation. It is common along the Lopez fault and the Little Tujunga fault for the Saugus beds to dip at rather gentle angles toward the overriding fault (plate 2). It is so common, in fact, that, in the absence of an exposure of the actual fault contact, to have the bedding dip gently toward the basement rocks may be taken as a valid criterion to infer the presence of such an overthrust fault. As suggested on the geologic map (plate 2), the thrust faulting between basement and sediments east of Loop Canyon may be the western end of movements along the Buck Canyon fault. The geometry of the northward-dipping thrust faults, most likely related to deformation associated with the San Gabriel fault and diminished offsets at their southwestern ends, provides additional support for considering the faulting west of Pacoima Canyon to be analogous to that to the east.

It is now appropriate to look at the exposures of the contact in Loop Canyon that Oakeshott (1958) defined as the type locality for the "Hospital fault." The large roadcuts along the May Canyon truck trail provide practically continuous exposures of the geology north of the Veterans Administration Hospital. Even though the Pacoima Formation is a very coarse sedimentary breccia at this locality, the excellent exposures made it possible to determine the attitude of rude bedding in the formation. The continuation of the syncline visible east of Loop Canyon was easily mapped along the road.

Near the contact with the basement rocks, the coarse Pacoima debris dips 60° to 70° S. and is separated from the granodiorite by a thin sequence of medium-grained, sandy sedimentary breccia beds interlayered with beds of coarser debris. Oakeshott (1958, photo 66) interpreted this finer grained deposit to be Saugus Formation and concluded that the Pacoima sits unconformably on it here; however, as can be seen in his photo, there are coarser beds interlayered with the finer debris. These coarser beds are lithologically identical to the thicker Pacoima beds a few feet higher in the section. Furthermore, the material composing the finer light-colored sedimentary breccia is very angular and, in hand specimen, appears to be lithologically identical to the granodiorite directly in contact with it. There has been faulting at this locality, and a zone of gouge and/or caliche about 3 cm (1 inch) thick that dips 82° S. separates the basement rock from the sediments. This contact can be followed westward over a low ridge to the western slope, where it is also exposed and dips 60° south. No reverse faulting was observed between the basement and the Pacoima Formation, although there are several faults with various attitudes within the fractured basement rocks. The dip of the Pacoima beds is away from the basement, and the material closest to the contact appears to be very locally derived. This suggests that perhaps the Pacoima has been folded as the frontal portion of the mountains rose and tilted toward the south, rather than being thrust over the sediments.

Cropping out about 30 m (100 feet) north of the contact along the truck trail are extremely sheared, no longer identifiable basement rocks now expressed as a zone of gritty, greenish gouge containing what appear to be crushed white and pink remnants of granitic dikes. A special symbol is used on the geologic map to indicate that the attitude of shear planes in these outcrops is variable. The dip, however, is uniformly to the west, ranging from 10° to 50°. This highly sheared zone continues northward along the road and is well exposed east of the road on a small ridge that extends into the canyon. Material of this kind was not found on the east wall of Loop Canyon, nor could it be traced very far to the west. It is suggested that this shear zone represents ancient tectonic movements. The present outcrop pattern suggests that this zone is a "fossil" fault zone and is probably unrelated to the more recent diastrophism involving the rise of the San Gabriel Mountains during Pleistocene time.

The straightness of the contact across rugged topography east of the canyon north of the May Canyon debris dam, also observed by Merifield (1958), implies a very steep boundary between the basement and Pacoima rocks. The chaotic nature of the Pacoima Formation makes it difficult and, locally, impossible to determine the attitude of the unit. In the lower portion of the formation, west of the syncline near Loop Canyon, the bedding is better developed and dips moderately and consistently toward the basement. However, the dips obtained closest to the contact range from 70° to 90° north. Where exposed, the contact has all the appearances of being a depositional one with the sediments resting on granodiorite and foliated dioritic rocks. Nevertheless, as the sparse attitudes and geometry of the trace indicate, the contact must be a steep to vertical fault from Loop Canyon to the north-trending canyon behind May Canyon debris dam (plate 2).

From this canyon west to Wilson Canyon, the Pacoima Formation is in depositional contact on a variety of basement rock types. A continuation of the gentle frontal syncline reappears; and the trace of the contact is irregular on the map, reflecting the low to moderate dips of the Pacoima rocks. The Pacoima Formation in this vicinity is covered locally by the remnants of a dark red deposit of alluvial fan debris that has been dissected and partially eroded away. This alluvial fan deposit is very similar in appearance to the Pacoima Formation and no doubt formed under similar conditions; however, the fan rests unconformably on the synclinally folded Pacoima beds and is, therefore, younger than the Pacoima Formation.

Conjectural Fault East of Olive View

Intensive mapping of the geology along the mountain front has revealed that the contact between the basement rocks and the Pacoima Formation, described by Oakeshott (1958) as the Hospital fault, changes from a steep south-dipping to vertical normal fault to depositional. Present exposures do not provide any evidence for a north-dipping thrust fault of the Sierra Madre system between Loop Canyon and Olive View. This observation leads to the question, if such a structural relation exists between the basement rocks and the younger sedimentary rocks along this portion of the San Gabriel Range as it characteristically does elsewhere east and west of here, just where could it be?

The conjectural fault east of Olive View as shown on the geologic map (plate 2) is based upon a variety of circumstantial evidence. This evidence does no more than suggest the presence of conditions which can be ascribed to faulting. The conjectural fault is also based upon the present high elevation of the basement rocks and folding in the nearby sediments which may imply such a structure. The evidence is sufficient only for speculation on such a fault. To prove or disprove the existence of this hypothetical fault, it would be necessary to employ geophysical and other methods to investigate the hidden geology in this vicinity.

Nevertheless, the circumstantial evidence for this conjectural fault is abundant and consists of several different kinds of features. Between Olive View and the canyon north of May Canyon debris dam, an abrupt topographic scarp trends toward the northeast along the base of the uplifted and dissected alluvial fan deposits which overlie Pacoima and Saugus beds. The best development of this scarp is just east of Wilson Canyon channel along the front of the flat where the long, tile-roofed building is situated. Here the scarp is approximately 12 to 15 m (40 to 50 feet) high. About 244 m (800 feet) east of Wilson Canyon channel, the concrete structure of the Maclay High Line Aqueduct was damaged where it intersects the scarp and had to be excavated and repaired there. The scarp has been dissected by a small canyon about 488 m (1600 feet) east of Wilson Canyon channel. Near the mouth of this small canyon, clumps of reeds lie on a line nearly coincident with the projected trend of the scarp. The reeds imply a near-surface water supply, possibly springs. Farther to the east, the scarp is discontinuous and appears to bend to a N. 60° E. direction across the slope on the fanglomerate deposits west of May Canyon debris dam. That the abrupt aligned changes in the topography suggest faulting is well demonstrated by the Tujunga segment of the San Fernando fault zone. While there may be alternative explanations for the development of the scarp described, faulting must be considered as an entirely possible cause.

Evidence from the mapped geology for the conjectural fault consists of the observed changes in structure both east and west of the canyon north of May Canyon debris dam. The high-angle fault that separates basement rocks from the Pacoima Formation does not continue west of this canyon. The change in strike of bedding across this canyon and the change in the elevation of the Saugus/Pacoima contact, as well, suggest that a fault may underlie the alluvium in the canyon. Not only is the geologic structure different but so is the geomorphology east and west of the above mentioned canyon. To the east, streams flow southwestward and westward toward this canyon; but only small gullies have developed on the west side. However, old alluvial fan deposits which cap the dissected ridges in the Pacoima and Saugus Formations are dramatically different in degree of preservation on the west of this canyon, where the drainage is also well developed toward the southwest, implying a tilting in that direction. The implication that the differences in these features may have been the result of differential structural histories on either side of this canyon supports the concept of a fault separating them as shown on the geologic map.

Veterans Fault

This fault (47) has received much attention because it is the only example of surface faulting that could be found associated with the earthquake in the area between Pacoima Wash and Olive View near the mountain front. Very detailed mapping has not disclosed any additional, similarly notable, tectonic features; but it has expanded the previously mapped limits of surface breakage beyond the well-defined scarp of the Veterans fault.

Surface faulting has different aspects where the surficial materials change along the trace of the Veterans fault. A well-defined 15-to-20 cm (6-to-8 inch) high scarp (photo 15) could be followed about 300 m (1000 feet) across graded bedrock surfaces from Wallaby Avenue to Graber Avenue. The scarp terminated on the eastern end against a scarp formed by the settlement of artificial fill. On the west, between Graber Avenue and Candlewood Drive, the faulting did not produce a continuous scarp; but it could be followed as an alignment of humps, cracks, and damaged houses. This 120 m (400 foot) stretch transects artificial fill and stream channel deposits of Loop Canyon. Possibly, the lack of well-expressed surface breaks in these unconsolidated materials is similar to that discussed in relation to the surface expression of the Oak Hill fault.

Photo 15. Veterans fault scarp where it was best developed east of the corner of Tucker Avenue and Rajah Street. Scarp is 15 cm (6 inches) high across a graded bedrock surface. Pencil leaning on scarp for scale.

West of Candlewood Drive, surface breakage could be traced discontinuously except for the low scarp on top of the old alluvial fan deposits which could be followed for 120 m (400 feet) to within 390 m (1280 feet) of the collapsed Veterans Administration Hospital buildings. This low scarp is only 1 to 5 cm (0.5 to 2 inches) high (photo 16). It is debatable whether the surface breakage west of Candlewood Drive is a manifestation of movements along a continuation of the well-defined Veterans fault to the east. There are certain similarities in surface expression which are noted below although the western faulting does not appear to be parallel to bedding in the Saugus Formation as is that along the Veterans fault.

Photo 16. Western end of surface breakage across surface of old alluvial fan deposits approximately 400 m (1300 feet) east of the collapsed main buildings at the Veterans Administration Hospital. The scarp is 1 to 5 cm (0.4 to 2 inches) up on the north. This surface fault may be related to movements on the buried possible western extension of the Veterans fault. *Photo by F. Harold Weber, Jr.*

The eastern portion of the Veterans fault parallels the north-dipping bedding planes in the Saugus Formation; and, from Graber Avenue to Wallaby Avenue, the Saugus Formation has been faulted against later Quaternary terrace deposits. The terrace deposits, which rest on tilted Saugus beds, are 4 to 6 m (15 to 20 feet) thick at the fault as measured in the cuts on the east side of Graber Avenue. This indicates that faulting has occurred on the Veterans fault many times in the relatively recent past.

Prior to the grading of the terrain traversed by the Veterans fault, several terrace levels were visible there. Miller (1928, plate 32b) presented a photograph which shows these terraces. Oakeshott (1958, p. 87–88) also noticed these terraces and made specific reference to them: "Five distinct steps, easily seen on the west side of Pacoima Wash and well marked on the 1:24,000 Sylmar topographic map, actually represent five stages of deposition, although the oldest and youngest are separated only 250 feet in elevation." Using the 1935 map, to which Oakeshott referred, and the photograph presented by Miller, it is possible to plot the boundaries of these terrace levels quite accurately. Superimposing these boundaries on the modern topographic map at the same scale and plotting the trace of the Veterans fault reveals a nearly perfect correlation between the boundary of the second and third levels upslope and the trace of the fault. The lack of this many terrace levels immediately north of the small canyon north of Wallaby Avenue, where one would expect the erosional and depositional regimes to be almost identical, supports the conclusion that faulting on the Veterans fault created two levels from the same original surface. Naturally, without exposures of the fault, this extra level would be interpreted as another terrace. Topographic suggestions of relatively young faulting are much more easily perceived on the older topographic maps because of the 5- and 25-foot contour intervals used on them. Additional examples of the utility of these maps are given by Weber (this Bulletin).

Many have searched for evidence of the continuation of the Veterans fault both east and west of its surface expression. To the east, no evidence of faulting was found in Pacoima Wash or across the paved road east of the wash or within the outcrops of Saugus Formation. Pacoima Wash, of course, is filled with loose, coarse alluvium which could easily disperse the effects of faulting of the magnitude of that which developed along the Veterans fault.

Interpretations, by others, of the various earthquake-produced features beyond the western end of the well-developed scarp which extends to Graber Avenue are different from those presented below. Kamb and others (1971, p. 51) show a dashed continuation on their map and state that "a southwestward extension of about 250 m beyond the recognizable scarp is defined by a zone of major structural damage to houses." The U.S. Geological Survey staff (1971, p. 72) also were of the opinion that faulting might continue toward the southwest, noting that "a short scarp with vertical offset observed on Hubbard Street [Gavina Avenue] would have a southwesterly trend." They also considered an alternative interpretation of the break across Gavina Avenue, saying that "although the rupture has the appearance of a tectonic feature, it conceivably could represent the bulged toe of an unexpectedly large landslide whose upslope limits have not been recognized."

Those surface effects which extend to the southwest across Gavina Avenue and continue across numerous streets in a line almost parallel to and just east of Hubbard Street consist of unusually heavy damage to houses (Kamb and others, 1971) and of numerous cracks across streets and curbings. These effects are shown in plate 3. Comparison of the geologic (plate 2) and surface effects maps (plate 3) shows that this zone of effects corresponds to the boundary between old alluvial fan deposits and alluvium. This pre-existing change in slope, which is still visible trending west across a field southwest of Simshaw Avenue, was modified during grading operations; and differential movements in the materials underlying this area were probably responsible for the stronger surface effects. The break on Gavina Avenue referred to by the U.S. Geological Survey (1971) overlies the buried boundary of the old channel of Loop Canyon; and, therefore, it, too, may be a result of differential response of natural materials and artificial fill.

The interpretation that the Veterans fault surface breakage continues to the west rather than to the southwest is based upon both observed earthquake-produced effects, some of which are enumerated above, and on very detailed geologic mapping by F. H. Weber, Jr., in the vicinity of the hillside west of Candlewood Drive. The Saugus Formation is well exposed in the large roadcut at the bend in Hubbard Street. The Saugus beds are unconformably overlain by alluvial fan deposits which underlie the entire Veterans Administration Hospital site. The contact between the Saugus and fan deposits can be followed northward to a southeast-trending gully about 90 m (300 feet) north of Hubbard Street. This gully contains slope wash debris and thick brush which conceal the contact. It is exposed, however, on the north side of the gully. This contact appears to be a minimum of 7.6 m (25 feet) higher there than it would be if it were projected from the place where it is last seen on the south side of the gully. These observations have been interpreted as the locus of a fault which exhibits similar total vertical displacement to the Veterans fault farther east. Excavation of the debris in the gully would remove the current ambiguities in the interpretation. The fault, described above, which strikes across the flat (photo 16) can be traced directly to this gully. Although there are minor cracks at various places on the Veterans Administration Hospital site, no other surface faulting was observed near the hospital buildings.

Additional Surface Effects West of Pacoima Wash

The features associated with the Veterans fault have received much attention because they are the only recognized expression of surface faulting in the vicinity of the tragedy at the Veterans Administration Hospital. Elsewhere along the mountain front, however, two other kinds of surface effects were observed which provide a record of the severe ground motion there. Of these two, shattered ridge tops are less common but are identical in appearance to those already described east of Pacoima Wash where they are relatively abundant. North of the Veterans fault and north of Wallaby Avenue (48), there is a remnant of original terrain that was left unmodified during the grading operations in the area. This low ridge is underlain by north-dipping beds of the Saugus Formation with a thin veneer of Quaternary terrace deposits on top. These terrace deposits were violently disrupted and shattered during the earthquake (photo 17). Although shattering is not common in this area, it does occur elsewhere. In Loop Canyon north of the Pacoima-basement rock contact, two narrow ridges of dioritic gneiss, capped by thin terrace deposits, are likewise shattered (45). Other terrace deposits in this vicinity are not shattered.

Photo 17. Shattered terrace deposits north of Walloby Avenue and about 122 m (400 feet) north of the Veterans fault (locality 48, plate 3). In the foreground, the roofs of houses under construction fell toward the north during the earthquake. *Photo by F. Harold Weber, Jr.*

Probably, the shattering was localized at these places because the combination of a narrow bedrock ridge capped by thin terrace deposits provided the necessary conditions. Shattering on Sugarloaf (108) east of Lopez Canyon also occurred in terrace deposits overlying Saugus beds. In detail, shattering there developed only where the terrace deposits are thin and the ridge top is relatively narrow. In contrast, shattering did not appear to develop on the top of Sugarloaf (108), where the terrace deposits are thicker and the ridge is broader.

Shattered ridge tops are not common between the Veterans Administration Hospital site and Olive View probably because the appropriate geological and topographical conditions are not present there. A few narrow ridges underlain by north-dipping Pacoima beds are shattered just west of the Veterans Administration Hospital site.

Slope failures are much more common than shattering in this area. The typical failure is characterized by the downslope movement of soil predominantly on the north sides of east-west-trending ridges. This effect is especially common on the north slopes of ridges in the Pacoima Formation east of Olive View Hospital (plate 3). One uncommonly large landslide did occur west of Loop Canyon (plate 3). The edge breakage in old alluvial fan deposits northeast of the Veterans Administration Hospital is a typical example of bank failure (photo 18).

The permanent change in the shapes of man-made structures relative to their surroundings provides a record of the vector of greatest ground motion during the earthquake; for example, the main Olive View Hospital building, the roofs of collapsed, partially constructed houses near the Veterans fault (photo 17), a large log lodge north of Wilson Canyon debris dam (photo 19), and many of the older structures at the Olive View site that moved off their foundations and were not built on filled ground. All of these structures provide an indication of the inertial effect on structures which were unable to return to their original location or shape after the passage of earthquake ground waves. The predominant failure of north-facing slopes in this vicinity is analogous.

CONCLUSIONS

The myriad surface effects of the San Fernando earthquake have been intensively investigated and recorded in great detail. During the study of the geology of the area where the effects are most abundant, heavy emphasis was placed upon learning about those features which might have indicated, before the earthquake, something about what could have been expected. Major structural features were also examined because their position or orientation and inferred structural history is analogous to that of structures that were active during this event. The greatest utility of this work will be in the application of what has been learned here to other areas where youthfulness of surface faulting is suspected. Many of the observations and conclusions from this study are presented in the following list.

Little Tujunga Canyon to Pacoima Wash

1. Movements on the Tujunga segment of the San Fernando fault zone created abundant scarps, ridges, mole tracks, and cracks that were concentrated along the base of the foothills between Little Tujunga Canyon and Pacoima Wash.

2. Surface faulting along the Tujunga segment is expressed over a relatively broad zone extending as much as hundreds of feet north of the compressional scarps at the edge of the thrust.

3. In addition to the predominant dip-slip component, a significant left-lateral component of displacement is characteristic of most of the surface faulting within this area.

4. Surface faulting on such faults as the Kagel, which transects the strike of enclosing strata, and the Oak Hill, which parallels bedding, was widespread

Photo 18. Edge breakage and northeast-facing slope failure in old alluvial fan deposits at the Veterans Administration Hospital site. *Photo by James E. Kahle.*

Photo 19. View east at a log lodge north of Wilson Canyon flood control dam and 670 m (2200 feet) north of the main building at Olive View Hospital. The inertial effect of severe ground motion on the roof has offset the roof N. 24° E.

north of the Tujunga segment, mostly within 1200 m (4000 feet) of the frontal scarps.

5. Damage from surface faulting in the Tujunga segment was restricted to roads and utilities and affected very few buildings because of the sparsity of buildings in the area.

6. The best-developed scarps resulting from surface faulting cross areas that had been artificially graded so that bedrock was exposed.

7. A record of previous faulting on the Tujunga segment was revealed in a trench which exposed more than 13 m (43 feet) of Tertiary sedimentary rocks overlying alluvium.

8. At one locality, the juxtaposition, by faulting, of slope wash deposits over alluvial material along the Tujunga segment implies very youthful movement prior to the earthquake on this fault zone.

9. Trenches excavated across mole tracks in unconsolidated alluvium were of little or no value for determining details of faulting because of the absence of marker units which might have been displaced.

10. Application of the techniques of very detailed mapping (scales as large as 1:2400) to the search for potentially active or young faults would have revealed, in natural as well as artificial exposures, both the existence and the youthfulness of the Tujunga fault segment before the earthquake.

11. The highest scarps and greatest offsets on the Tujunga fault segment occur toward its eastern and western ends. It is probable that the different aspect in the central portion, characterized by multiple scarps, is a result of movements along the Kagel fault.

12. No reactivation as a result of the earthquake was observed on the Little Tujunga fault, the Lopez fault, or Buck Canyon fault—all members of the Sierra Madre fault system, which separates basement rocks from Pleistocene sedimentary rocks.

13. The above-mentioned faults are covered in many places by old fan and terrace deposits which are undisturbed. The youthfulness of the rocks involved in faulting along the Tujunga segment implies a change in activity in relatively recent time toward the southernmost fault of the Sierra Madre "family".

14. Comparison of the geologic map and surface effects map demonstrates the lithologic and topographic control over the distribution of landslides and rockfalls.

15. Reactivation of the very large landslides that characterize the basement terrain north of and across faults of the Sierra Madre system was very limited. Debris in some of these slides moved from shaking, but the slides did not move downslope as a body.

16. All of the large rockfalls did not occur at the time of the main earthquake. Those that fell later, especially large ones near Pacoima Dam, are examples of geologic hazards that must be recognized and iden-

tified during rapid reconnaissance of the area affected by the earthquake by experienced personnel.

17. The surface breakage associated with differential settling of artificially filled land relative to natural ground was particularly damaging to roads and other paved areas.

18. Shattered ridge tops that resemble plowed ground are a spectacular and relatively widespread feature of this earthquake and are indicative of a concentration of shaking energy. This feature was localized along the tops of angular peaks or ridges where soil or terrace cover is thin. It also developed in sandstone strata on sharp ridges.

19. Earthquake effects were concentrated along the contact between the Towsley/Pico and Saugus Formations. Shattered ridges, strong shaking reflected in heavy damage to structures and water tanks, ground cracks and minor bedding-plane faults are all much more abundant in the vicinity of this contact. Post-earthquake surveying data, gathered by others, support the field observations of a concentration of effects along this contact by indicating that the area of greatest permanent change in elevation coincides, in general, with this contact.

Pacoima Canyon to Wilson Canyon

1. The only example of surface faulting near the mountain front in this vicinity is the Veterans fault, which can be traced as a well-defined scarp for 300 m (1000 feet) across an artificially graded bedrock surface and for an additional 120 m (400 feet) across fill and alluvium.

2. Along the Veterans fault, Quaternary terrace deposits are 4 to 6 m (15 to 20 feet) thick where they are juxtaposed against Saugus Formation, providing a record of previous youthful activity on this fault.

3. Before grading of the terrain traversed by the Veterans fault, topographic evidence was ambiguous and was logically interpreted as a change in level between two terraces where there appeared to be five such levels.

4. West of the surface effects directly associated with the Veterans fault, a low fault scarp that crosses the flat surface of an old alluvial fan can be traced to within 390 m (1280 feet) of the Veterans Administration Hospital. An apparent offset, a minimum of 7.6 m (25 feet), of the contact between Saugus Formation and overlying alluvial fan deposits in a gully at the eastern end of this scarp suggests prior youthful activity on this fault similar to that cited above along the Veterans fault.

5. Northeast of the Veterans Administration Hospital, the basement complex has been thrust over Pleistocene Pacoima Formation along a fault that dips 20° N. North of the Veterans Administration Hospital, the Pacoima rests on basement rocks in a depositional contact. West of Loop Canyon to the canyon north of May Canyon debris dam, the contact between basement rocks and Pacoima Formation is a steeply south-dipping to vertical normal fault. West of this canyon, the Pacoima Formation sits depositionally upon the basement rocks and is unconformably overlain by an uplifted and dissected alluvial fan.

6. A conjectural fault has been inferred on the basis of a topographic scarp and geologic relations along the base of the foothills between Wilson Canyon Channel and the canyon north of the May Canyon debris dam.

7. In this region there was no surface faulting resulting from the earthquake along the basement-sedimentary rock contact or along the trend of the conjectural fault.

8. The heavy structural damage in this vicinity was related to severe shaking. The failure by edge cracking and downslope movement, especially of north-facing slopes, is analogous to the effects exhibited by man-made structures which were unable to return to their original location or shape after the passage of the initial earthquake ground motion. These features recorded the inertial effect of bodies subjected to a south- or southwest-trending vector of ground motion.

Surface Effects and Related Geology of the Lakeview Fault Segment of the San Fernando Fault Zone

by James E. Kahle [1]

ABSTRACT

The San Fernando earthquake was caused by movement on a zone of thrust faults dipping northward into the San Gabriel Mountains. The movement was accompanied by surface faulting which was subsequently mapped as several separate fault segments collectively named the San Fernando fault zone. One part of this fault zone, called the Lakeview fault segment, is described in this report.

Such evidence for surface faulting as vertical displacement, cracking adjacent to the scarp, and landsliding along the trace is compelling and is discussed in detail. It was necessary to map the related geology in detail to establish the character and magnitude of previous faulting on the thrust. Gathering the evidence needed to delineate the fault trace and to understand the geologic history of the thrust was facilitated by the excellent exposures formed by fault-triggered landslides. At least 475 m (1550 feet) of pre-earthquake movement was measured on the fault. An attempt was made to evaluate the evidence available, exclusive of surface effects, to determine whether the fault might have been recognized as active prior to the earthquake. Its age could have been determined as Holocene; its potential for renewed activity would have been recognized; but no consensus regarding its potential for disaster could have been expected.

In the San Fernando earthquake of February 9, 1971, surface faulting occurred, rather unexpectedly, from the area north of Mission San Fernando to Sunland on an alignment subsequently called the San Fernando fault zone. Surface faulting on the Santa Susana fault zone is described elsewhere in this Bulletin (Weber; Saul). The Lakeview segment of the San Fernando fault zone, here called the Lakeview fault, broke the surface of the ground over a linear distance of 6.8 km (4.2 miles) between Kagel Canyon and Big Tujunga Canyon (shown on plate 2 in red and on plate 3). Rocks of Miocene age were thrust upward and south-southwestward an average of 80–120 cm (2.5–4.0 feet) over rocks of Holocene and/or Pleistocene age in this earthquake. Surface faulting occurred along a complex, north-dipping fault plane which trends approximately N. 70° W. Scarps were formed in the alluvium of Tujunga Valley and along the frontal slopes of the foothills westward across ridges, hillsides, and canyon bottoms as far as Kagel Canyon. Many small landslides and other surface effects mark the trace of the fault in the hills north of Tujunga Valley.

[1] California Division of Mines and Geology, Los Angeles.

The hilly area covered in this report is not heavily developed; consequently, damage was relatively light as compared to other areas affected by the earthquake (Weber, this Bulletin; Slosson, this Bulletin). Several houses, utility lines, and roads in Kagel Canyon and the roads and utilities in Little Tujunga Canyon and Big Tujunga Canyon were damaged by surface breakage on the Lakeview fault.

Detailed mapping of the surface breaks and the related geology has been in progress since the earthquake. The purpose of this mapping was a) to record as fully as possible the surface breaks and other surface effects formed at the time of the earthquake (plate 3); b) to identify any potentially hazardous conditions caused by the earthquake; and c) to understand the complex geological history of this well-exposed active thrust fault.

These studies will provide a data base for continuing observations of the long-term effects of the earthquake on this area. Observations of the climatological modification of the disturbed ground surface—especially in areas where potential hazards from landslide, mudflow, and rapid erosion might develop—will be necessary for many years. A clear understanding of the detailed geology of this once poorly recognized and very complex part of a larger active fault system may help in the identification of other as yet unrecognized active faults in California. Hopefully, it will also provide some information on how often future earthquakes are likely to occur in this and other areas if enough is learned about its history.

The detail shown along the Lakeview fault on plate 2 is only representative of the complex geology and does not imply that the work is complete enough to serve all the above purposes. Enough has been done to demonstrate the great value of such detailed work and to provide a firm foundation for future observations and continuing study.

The earthquake called attention to the complex geologic setting of the Lakeview fault and made it necessary to modify much of the existing geologic mapping. Approximately 2 km (1¼ miles) of the Lakeview fault had been recognized before the earthquake and discussed in an unpublished report (Jahns and others, 1970). Surface faulting coincided with some sections of other previously mapped faults (Barrows; Weber; Saul; this Bulletin) but at only a few places in the area of this report. Significant differences in the interpretation of the geology are discussed in the sections on rock types and structure. Minor differences are discussed in the section on surface effects.

The general geology of the area between Little Tujunga Canyon and Big Tujunga Canyon is outlined briefly in the sections on descriptive geology and structure. More detailed discussions are included for the area immediately adjacent to the Lakeview fault.

The major part of this report concerns the varied surface effects of the San Fernando earthquake in the region between Little Tujunga Canyon and Big Tujunga Canyon. Surface faulting, the most significant effect, is described from west to east a short section at a time. Such additional effects, as cracks in soil, landslides and rockfalls, shattered ridges, and failure of fills are discussed under separate headings. Where these effects are adjacent to the surface faulting, they are included with the sectional descriptions.

Numbers, alone and within parentheses in the text, refer to localities on the surface effects map (plate 3). Measurements indicated on this map, in the Lakeview fault area, are accurate within ±2 cm (¾ inch) in most cases.

DESCRIPTIVE GEOLOGY

Pre-Tertiary Rocks

The pre-Tertiary rocks of the basement complex are described fully by Oakeshott (1958) and by Ehlig (this Bulletin). These are the source rocks for most of the Quaternary deposits described in this report. Because of the wide variety of rock types present, it was not feasible, in the present study, to try to identify any specific source areas for particular deposits.

Tertiary Rocks

Topanga Formation. The only rocks of the Topanga Formation exposed within the mapped area are basalt flows north of the Sunland fault. Most of the geology shown on plate 2 in this vicinity was compiled from Beatie (1958) who described the Topanga Formation in considerable detail. Oakeshott (1958, p. 64) characterized these rocks as "black compact vesicular basalt with no visible phenocrysts . . . in a series of flows alternating with beds of coarse reddish-brown breccia." Sharp (1934) mapped part of the Modelo Formation, shown on plate 2 north of the Sunland fault, as rocks of the Topanga Formation. He also mapped some of the patches of Modelo to the west as Topanga rocks, but the more recent work was followed for this report.

Modelo Formation. Rocks of the Modelo Formation above the Lakeview fault are mostly thin-bedded, silty, and occasionally siliceous shale interbedded with fine-grained arkosic sandstone. A few thin diatomaceous shale beds and minor arkosic conglomerate beds are present. These rocks are probably correlative with the middle or upper part of the Modelo Formation to the west. Rocks, probably correlative with the lower part of the Modelo Formation, crop out below the Lakeview thrust from Schwartz Canyon eastward to the Lakeview Terrace Sanitarium. Beds of coarse- to fine-grained, buff to yellowish-brown arkosic sandstone and pebble conglomerate predominate here. Siliceous shale beds of the Modelo Formation are in fault contact with, and underlie, silty shale and sandstone beds of the Modelo Formation on the slopes immediately east of Little Tujunga Canyon.

Towsley/Pico Formation (undifferentiated). Conglomerate, sandstone, and dark gray shale overlying the Modelo Formation conformably in this area are referred to as Towsley/Pico Formation. These are called the Repetto Formation by Oakeshott (1958) and may be correlative with rocks of the Towsley Formation farther west; meager collections of early Pliocene fossils in the Little Tujunga area were made by Hill, Oakeshott, and Howell (Oakeshott, 1958, p. 79). Steep cliffs formed by the resistant conglomerate beds of the Towsley/Pico Formation characterize the contact with soft shale beds of the Modelo Formation. Large landslides in the shale beds along this contact commonly contain large blocks of the conglomerate. Several of these landslides were partially reactivated during the earthquake. An exceptionally large one in Schwartz Canyon (plate 2) had a fresh 10 m (32-foot) scarp at its head near the ridge top. In places, the toe of the slide dammed the stream channel.

Saugus Formation. The area underlain by the Saugus Formation was not mapped in detail. It is characterized by poorly to moderately consolidated, light-gray pebbly conglomerate and medium- to coarse-grained sandstone with interbedded, reddish-brown mudstone layers. Beatie (1958) and Oakeshott (1958) described the Saugus Formation fully.

Quaternary Rocks

"Thrust sequence". Young rocks, probably late Pleistocene through Holocene, have been overridden hundreds of meters by rocks of Miocene age to form the stratigraphic sequence which helps to identify the Lakeview thrust fault. This closely related sequence of rocks under the thrust plane is called the "thrust sequence" in this report for convenience. It is a distinctive and mappable unit and may be analogous to other rock sequences perhaps present under other active thrust faults in adjacent areas. This sequence of rocks is as vital to the interpretation of the Lakeview fault as the surface breaks. Three members, whose contacts are largely gradational, can be conveniently differentiated. In this report and on plate 2, they include an older alluvial terrace gravel (Qot); a mixed sedimentary unit called alluvium-breccia (Qab); and a breccia unit (Qbx) which is believed to be largely tectonic but partly sedimentary in origin. The inferred age of this sequence ranges from the present to more than 60,000 years old and is probably much older. The evidence for this age is discussed in the section on the Lakeview fault.

Older terrace gravel. The older terrace gravel is an unconsolidated to poorly consolidated unit consisting of interbedded boulder gravel and bouldery cobble-to-pebble gravel which is 25–30 m (80–100 feet) thick containing discontinuous lenses and layers of coarse-grained sand and fine-pebble gravel. Bedding is vague to invisible and very irregular, both laterally and vertically. In both composition and texture, this unit closely resembles the alluvium of Big Tujunga Wash and Tujunga Valley, suggesting a similar source and fluviatile deposition. Igneous and metamorphic clasts, most likely derived from the basement complex to the north, predominate. Clasts of anorthosite are common. A few volcanic clasts and rare clasts of sedimentary rocks which resemble rocks of the Modelo Formation or Towsley/Pico Formations are present.

Outcrops of older terrace gravel are nearly continuous along the front of the foothills between Little Tujunga Canyon and the Lakeview Terrace Sanitarium. East of Schwartz Canyon, the base rests on eroded and truncated beds of the lower Modelo Formation 25–35 m (80–115 feet) above the base of the hills. Westward from Schwartz Canyon, the base of this unit is buried by modern alluvium. Most of the unit is not covered since the thickness of the exposed part is still greater than 25 m (80 feet).

The older terrace gravel thickens to 30 m (100 feet) or more along the base of the hill east of Little Tujunga Canyon where shale of the Modelo Formation appears to be in fault(?) contact above it. This ancestral part of the Lakeview fault zone did not move during the earthquake. Higher on this hill another imbricate, and possibly contemporaneous, sequence of terrace gravel lies depositionally on top of the first shale unit. More shale of the Modelo Formation lies above this gravel unit, also in fault(?) contact, suggesting a sequence of imbricate thrust faults which is discussed more fully below (plate 2).

This unit has been mapped previously as terrace gravel but only as remnants of a partly eroded surface deposit along the base of the hills (Sharp, 1934; Howell, 1949; Beatie, 1958; Oakeshort, 1958). At one locality, just west of Oliver Canyon (129), Oakeshott showed rocks of the Modelo Formation thrust over older terrace gravel with the fault dipping north 60°. Howell showed the same fault dipping 64° N. but within rocks of the Modelo Formation.

Alluvium-breccia. This unit is probably transitional between the older terrace gravel and the breccia unit of the "thrust sequence." It is well exposed by recent slides. Beds containing clasts of well-rounded fluviatile sand and pebble-size material derived from the basement complex are mixed with angular pebble-size shale clasts derived directly from the nearby Modelo Formation. The percentage of silt- and sand-size material is greater in this unit than in the older terrace gravel or the modern alluvium, suggesting that some of this finer grained detritus may also have been derived from the Modelo Formation nearby. Bedding is vague to well defined. The unit is generally moderately consolidated to unconsolidated.

Another common type of bedding in this unit contains a high percentage of clay, silt, and fine-sand clasts mixed with coarse angular shale debris but contains only a few well-rounded clasts of basement rock. It closely resembles mudflow or debris flow material and is moderately well consolidated. Where not well exposed and seen only as surficial debris, it is easily mistaken for slope wash similar to that derived directly from the Modelo Formation. Locally, layers of caliche can be seen interbedded with these "flow" layers suggesting that this and the other mixed beds may have accumulated downslope from a nearby rapidly eroding area of moderately high relief. The present position and structure of the Lakeview fault supports speculation that an ancient fault scarp may have been situated a short distance to the north while these rocks were being deposited. This would probably be an area of high relief and a likely source of debris for contributing material to an area of general fluvial deposition. No well-defined contacts between this unit and those above and below it were observed. The lower contact is typified by a sharp change in grain size. The upper contact is probably gradational.

Breccia. The breccia unit consists exclusively of debris derived from shale of the Modelo Formation. The material in this debris was probably formed by brecciation of the Modelo shale during fault movement, but colluvium from this source appears to have been partly redistributed by sedimentary and mass wasting processes and to have accumulated in places as thick, wedge-shaped, vaguely bedded layers. It occurs only directly beneath the thrust plane. It is commonly white to light gray and very loose. Along a few of the higher ridges, it seems to have accumulated to a thickness of 5–10 m (15–30 feet), but in most areas it occurs as a thin discontinuous layer of brecciated Modelo shale less than 5 m (15 feet) thick. Although it may be present nearly everywhere along the thrust, only the thicker accumulations are shown on plate 2. In a few places, particularly where the thrust crosses canyon bottoms, it is apparently missing. This suggests that, where shale of the Modelo Formation has overridden the older alluvium and the mixed alluvium-breccia for only a short distance, significant brecciation due to fault movement has not had an opportunity to develop. At other locations, where faulting has occurred on bedding planes in shale of the Modelo Formation, little gouge or debris was seen. Perhaps gouge and fault breccia form best where unlike material is juxtaposed and the cumulative displacement is very large.

Older alluvium (undifferentiated). Many areas bordering Big Tujunga Wash and Tujunga Valley have small aprons of alluvial fan deposits and extensive deposits of inactive flood plain alluvium which appear to be unaffected by present-day flooding. These were combined on the map as undifferentiated older alluvium, except in a few places, and consist of sandy, boulder-to-pebble gravel very similar to that in the present-day stream channels. The fan deposits contain a limited variety of rock types reflecting the type of source material available in the separate canyons.

Older alluvial fan deposits. In the eastern part of the area, older apparently inactive alluvial fans have been differentiated from the older alluvium. The composition of these fans is somewhat different from most of the older alluvium. Clasts of dioritic rocks are very abundant, and in places these fans are nearly monolithologic.

Terrace gravel. Most of the terrace deposits are unconsolidated to poorly consolidated, fluviatile, bouldery, pebble-to-cobble gravel, and fine to coarse sand. They occur at widely varying elevations and have been differentiated from areas of older alluvium. In one location, just south of the Lakeview Terrace Sanitarium, there are three superposed levels of terrace deposits, probably closely related to previous faulting. Some terrace deposits along the Sunland fault appear to be displaced by fault scarps visible on air photos, and near Little Tujunga Canyon some of these are shown as hypothetical faults on the geologic map (plate 2).

Alluvium. The stream channels and active flood plains of Big Tujunga Wash, Tujunga Valley, and Little Tujunga Canyon contain sandy, pebble-to-boulder gravel. The clasts are well rounded and are mostly derived from the various basement rocks present in the areas drained. Some very large boulders, old bridge debris, and pieces of culvert in Tujunga Valley indicate the torrential nature of occasional floods.

STRUCTURE

Introduction

The surface breaks formed along the Lakeview fault at the time of the earthquake are prima facie evidence of its existence. The equally important geological evidence of major thrusting in this area is discussed in this section. The portion of the Lakeview fault that had been mapped prior to the earthquake moved again during this earthquake. Surface faulting occurred in many places where no faults had been mapped before, and the near-continuity of some of these breaks permits a four-fold extension of the known length of the Lakeview fault.

Other geologic features, now exposed by landsliding and therefore more easily recognized than before the earthquake, have provided a better opportunity to interpret the geologic structure than was previously possible. Most earlier work was done at scales designed to yield a regional understanding of the geology of much larger areas than that affected by movement on the San Fernando fault zone.

Three major faults are discussed here (which includes references to previous work): the Lakeview fault, the Wildwood fault (here considered part of the Lakeview fault), and the Sunland fault. Movement also occurred on the east end of the Tujunga fault segment; the structure of this area is discussed in the section on the Lakeview fault. For a more complete description of the Tujunga fault segment, see Barrows (this Bulletin).

Lakeview Fault

The Lakeview fault, as considered in this report, is a large thrust fault along which surface faulting occurred from Kagel Canyon to Big Tujunga Canyon. It was believed, for a time, that a series of disconnected scarps in several canyons was the only expression of faulting visible in this area and that any possible movement in the adjacent hills was masked by landslides (Kahle and others, 1971, p. 75; Kamb and others, 1971, p. 49; U. S. Geological Survey, 1971, p. 71). Very detailed mapping of the surface breaks in the hills revealed a surprising degree of continuity; and, though irregular and occasionally difficult to follow, when combined with the stratigraphic and structural evidence, the fault can be traced with confidence.

The Lakeview fault can be divided into two sections which have very different characteristics. Between Kagel Canyon and the alluvium of Tujunga Valley, the trace is sinuous and irregular and measures 6.8 km (4.2 miles) along the trace with a straight-line distance of 4.6 km (2.8 miles) from one end to the other. It parallels the front of the hills and is located an average of 0.4 km (¼ mile) north of and up slope from the base of the hills. The difference between the actual length of the trace and the straight-line distance is more than 2 km (1¼ miles) and is due to the low angle of dip of the fault plane intersecting the irregular topography. Eastward from the vicinity of the Lakeview Terrace Sanitarium, the trace is more nearly linear through the alluvium of Tujunga Valley and Big Tujunga Wash and can be followed as far as the north side of Bill Lane Camp (138), a linear distance of 2.3 km (1.4 miles). The average dip of the fault in the foothill section is 25° $\pm$ 10° N., but to the east it steepens to as much as 65° N.

Several kinds of evidence have been found which substantiate movement on the Lakeview fault. The trace in the hills is nearly continuous; and surface displacement, where visible, is consistent on both ridge tops and in the alluvium of the canyon bottoms—invariably up on the north. In Tujunga Valley, the trace is prominent and distinct, cutting both recent and older alluvium. Characteristic landslides, restricted to the trace, occur on many hillsides between Little Tujunga Canyon and the Lakeview Terrace Sanitarium. Shale of the Modelo Formation, which overlies the thrust, was moved outward on the slope enough to drop away as rockfalls and small landslides. Debris and dust have accumulated on the slopes below these breaks, simulating "skin-type" slides or thin soil failures. Commonly, the slope below the break is nearly undisturbed, except for flattened brush and cones of loose debris. In some places, material both above and below the thrust plane has fallen, providing excellent exposures of the Modelo-"thrust sequence" fault contact.

The "thrust sequence" occurs below the fault plane, in one form or another nearly everywhere, except in the alluvium of Tujunga Valley. The breccia unit is very thin or missing in many places and could only be shown diagrammatically on the map (plate 2). Weathering since the earthquake has changed the appearance of the breccia unit and the shale above the fault plane. The color contrast has been enhanced —the shale has turned dark brown; and the breccia, nearly white or light gray. The other units of the "thrust sequence" are also well exposed in many of the slides but are little changed, except for the removal of dust by wind and rain.

Between Oliver Canyon and Schwartz Canyon, the dip of the fault, inferred from the trace, is 20°–30° N. in the canyon bottoms. It changes gradually to nearly horizontal farther south until, near its southernmost extent (131), it dips approximately 10° S. The older terrace gravel of the thrust sequence in Oliver Canyon dips 10°–15° S. at the front of the hills and 10° N. beneath the trace near where it crosses the canyon bottom. This apparent "anticlinal" warp and the corresponding warp in the thrust surface suggest penecontemporaneous deformation of the thrust and the rocks under the thrust.

Remnants of terrace deposits, 25 m (80 feet) or more above the present stream level, are present from the Lakeview Terrace Sanitarium to the mouth of Akens Canyon, all at about the same elevation. They begin at the point where the fault leaves the hills and are north of the present fault scarp. It seems likely that they reflect previous episodes of activity on the Lakeview fault. The bluffs along Tujunga Valley probably represent a fault-line scarp; the terraces have been eroded northward and away from the fault in the alluvium to form the present cliffs. This area has been elevated so rapidly that Ebey Canyon and several small canyons which cut through the terrace deposits have a much steeper gradient where they enter Tujunga Valley. Their courses are similar to hanging valleys.

Erosion in several canyons has dissected the terrace deposits, but the terrace surfaces that remain are reasonably level. Many houses have been built here, but none was so badly damaged that it required demolition.

Rocks of the thrust sequence thin and may disappear east of the Lakeview Terrace Sanitarium. Two fault traces could be mapped in the alluvium of Tujunga Valley. These traces merge to one about 400 m (1300 feet) east (135) of where they first become visible. This suggests that rocks of the thrust sequence may pinch out beneath the surface in Tujunga Valley.

The evidence for previous large-scale displacement on the Lakeview fault is overwhelming. A 442 m (1450 feet) cumulative horizontal component of thrusting (heave) was measured from the ridge between Oliver Canyon and Schwartz Canyon to the point where the scarp crosses Schwartz Canyon. Shale of the Modelo Formation has been thrust southward over units of the "thrust sequence." This horizontal component may be extended 30 m (100 feet) from drill hole data which indicates shale of the Modelo Formation over gravel at a depth of 7 m (23 feet) about 18 m (60 feet) north of the fault trace in Schwartz Canyon (Proctor and others, 1972). The total heave measured is 475 m (1550 feet). The greatest vertical component measured (throw) was about 55 m (180 feet) from the fault trace on the ridge west of Oliver Canyon (130) to the canyon bottom; therefore, the minimum figure for displacement on the Lakeview fault is approximately equal to the heave.

The age of the rocks in the "thrust sequence" is inferred from their affinity to other similar rocks in the area. Bonilla (in press) found evidence allowing him to date tentatively a previous episode of faulting on a fault in Lopez Canyon which also moved in this earthquake. He suggests a recurrence interval of 200 years for such events. If we accept this figure and postulate a slip of 150 cm (5.0 feet) on the Lakeview fault for each previous event, the time needed to accumulate 475 m (1550 feet) of movement would be about 60,000 years. This may be close to the age of the base of the alluvium-breccia unit of the "thrust sequence." The older terrace gravel unit would be much older than that since it had to be deposited before movement on the fault began to influence the accumulation of the alluvium-breccia unit. Both the breccia unit and alluvium-breccia unit, therefore, appear to be time-transgressive, decreasing in age vertically and to the south.

The Lakeview fault segment and the Tujunga fault segment are quasi-imbricate and overlap linearly for about 2 km (1¼ miles) between Kagel Canyon and Cassara Canyon. This accounts for the double scarp in Little Tujunga Canyon. Displacements decrease and appear to die out on the west end of the Lakeview fault and on the east end of the Tujunga fault. The two segments do not join. The faults, which are about 350 m (1150 feet) apart, both dip north. A sequence of older, inactive, imbricate thrust faults has been tentatively mapped on the hill east of Little Tujunga Canyon, suggesting that the imbricate relationship of the Lakeview fault and the Tujunga fault has persisted in this area since its inception. Thrust faults are commonly mapped as more than one anastomosing trace, but the evidence above suggests that an en echelon imbricate pattern may be common and may persist for long periods of geologic time.

Other imbricate, probably sympathetic, movement has occurred within the "thrust sequence." Breaks, with a vertical component of displacement an order of magnitude less than those on the main trace, occurred between the older terrace gravel and alluvium-breccia unit east of Schwartz Canyon (133). Elsewhere, similar breaks suggest movement along the contact between the older terrace gravel and the alluvium-breccia unit, but they could not be traced for any great distance.

Surface faulting on the Lakeview fault coincided with only small portions of the faults shown on published maps. An unpublished geologic map (Jahns and others, 1970, plate 1), by the Metropolitan Water District of Southern California, delineated and named nearly 2.0 km (1¼ miles) of the Lakeview thrust prior to the earthquake. This portion of the thrust, between Oliver Canyon (128) and the Lakeview Terrace Sanitarium (134), broke essentially where it had been mapped, with minor variations (Proctor and others, 1972). Although this was compiled at a scale of 1:12,000, it is significant that the geologic interpretation necessary to identify this as a thrust fault resulted from mapping done at a scale of 1:4,800 (R. Crook, Jr., personal communication, 1971).

Oakeshott (1958, plate 1) shows a high-angle reverse fault (129) dipping 60° N. between rocks of the Modelo Formation and terrace gravel now recognized as part of the "thrust sequence." This part of the Lakeview fault broke during the earthquake, but the movement is involved in a reactivated "tectonic slide" portion of the thrust which will be discussed later. A small portion of a fault mapped by Howell (1949; 1954) corresponds with the location of the Lakeview fault in this same area (129). He projected it as a high-angle fault, from here across Oliver Canyon at approximately the same place that the Lakeview fault broke; but he then extended it northeast into rocks of the Towsley/Pico Formation.

The "Wildwood fault" was first named by Howell (1949, 1954), but a fault with the same general location and trend was shown on maps by Kew (1924, plate 1), Hill (1930), and Miller (1934). High-angle faults have been shown on maps by various authors through a saddle on the ridge east of Little Tujunga Canyon (119) in subparallel directions generally trending N. 65° W. as far west as Kagel Canyon and eastward to Cassara Canyon. Beatie (1958) shows a roughly coincident fault but does not name it. Jahns and others (1970, plate 1) essentially follow Beatie and Howell and call it the "Wildwood fault".

The "Wildwood" fault is not shown on plate 2 because it was located only approximately by previous workers. Moreover, the present surface breaks indicate a different direction and a much different character to the faulting here than that of the faults mapped previously. The Wildwood fault is considered here to be part of the Lakeview fault.

The Lakeview fault broke through the saddle on the ridge east of Little Tujunga Canyon as a low-angle thrust dipping less than 25° N. and striking approximately N. 75° W. subparallel to bedding. Legge (1937, plates 11 and 15) and Nolte (1937, p. 25–26) interpreted crumpled bedding present in a saddle (120) just east of this location (119) as a flexure instead of a fault. They projected this flexure on the same trend as some of the faults mentioned above. A minor fault did occur in this saddle (120) during the earthquake, but it could not be followed beyond the ridge crest more than a few feet. These "flexed" beds are now known to be located on the upper plate of the thrust, where such isoclinal folding could be intense. It seems to be more reasonable to interpret these aligned saddles as the locus of an active flexure. The nature of the faulting and folding interplay here may help explain some of the disagreement between different maps in this area.

Sunland Fault

No unequivocal evidence for 1971 movement was seen along the Sunland fault, a high-angle reverse fault; but ground breakage, shattered ridges, and particularly landslides and rockfalls north of the eastern end of the fault suggest the possibility of minor sympathetic movement or at least a concentration of severe shaking in the rocks of the upper plate. Rocks of the basement complex, patches of the Modelo Formation, and basalt of the Topanga Formation have been thrust over the Saugus Formation along the Sunland fault. The geology shown on plate 2 in the vicinity of the Sunland fault was compiled from Beatie (1958) and Oakeshott (1937; 1958; field maps). They have adequately described the feature, and the writer has supplemented the geology by air photo interpretation for possible evidence of faulting between Herreres Ranch and Gold Creek. Sharp (1934) suggested an interpretation of the northwestern end of the Sunland fault similar to that shown on plate 2 by extending it to Gold Creek.

SURFACE FAULTING AND SURFACE EFFECTS

General Features

It frequently is difficult to distinguish surface breaks due to faulting from those due to other causes such as lurching, differential settling, landsliding, or shattering of the soil layer. The criteria used to identify surface faulting are primarily continuity, amount of displacement, and linearity of the fractures, as well as displacement of rock units or fresh movements along bedding planes. Where the surface evidence is in unconsolidated material, as it most commonly is, the most important characteristics are continuity and the amount of vertical offset combined with any or all of the other criteria. The surface faulting present in this area is characterized by much associated ground cracking which is too dense to show on the map (plate 3). It is usually clear from the characteristic mole tracks and the displacement which series of breaks is the main surface fault.

Surface faulting on the Lakeview segment of the San Fernando fault zone can be traced from the ridge just west of Kagel Canyon to the hill on which Bill Lane Camp is located east of Big Tujunga Wash. The trace is nearly continuous, except where hidden by old landslides, thick accumulations of slope wash, or brush. Until sufficient detailed mapping of the trace and the related geology had been done, the continuity of the Lakeview fault was not well established and its imbricate but separate relationship with the Tujunga fault could not be verified (Barrows and others, 1971; Barrows, this Bulletin).

Many cracks which are not a direct result of surface faulting are, nevertheless, closely related to fault movement and are discussed with the descriptions of surface faulting. Other cracks and surface effects are discussed separately.

The surface breaks and other surface effects were mapped on 1:2400-scale air photos flown by American Aerial Surveys, Inc., on February 12, 1971, and on 1:4800-scale air photos flown along Tujunga Valley by I. K. Curtis Services on February 11, 1971. Some of the rockfalls and landslides shown on plate 3 were interpreted from other air photos flown four months later (Morton, this Bulletin) which were also used to map other surface effects north of the Lakeview fault area. The 1:2400-scale photos are barely adequate for recording all the major surface effects. Surface faults are shown on the geologic map (plate 2) in red and on the surface effects map (plate 3). Cracks, landslides resulting from the earthquake, and other surface effects are shown only on plate 3.

Detailed Descriptions

Kagel Canyon to Little Tujunga Canyon. Surface breaks on the Lakeview fault could not be traced beyond the ridge top west of Kagel Canyon where the road was broken. From the hillside west of Kagel

Canyon, the fault trace is nearly continuous eastward to Little Tujunga Canyon. The vertical component of movement increases eastward as far as the east side of Little Tujunga Canyon where it then decreases rapidly as the fault scarp disappears in landslide debris near the base of the hill. There are some cracks between the base of the hill and the top of the ridge east of Little Tujunga Canyon, but no continuity could be established.

Along the creek bottom in Kagel Canyon, a fence built of horizontal redwood boards bolted together at their ends appeared to be displaced vertically 25 cm (10 inches). Weathering marks on the partially rotated horizontal members of the fence allowed a reconstruction of its pre-earthquake position and indicated that one span had been built over a pre-existing sharp change in ground level at the point where the fault broke. This suggests that a previous scarp may have been present here and that the apparent vertical displacement was less in this event than could be measured on the ground.

In a small gully crossing the trace of the Lakeview fault west of the road in Little Tujunga Canyon (116), a small slide has exposed shale of the Modelo Formation lying on top of unconsolidated bouldery cobble gravel (photo 1). These units are in fault contact; and, although the fault moved in this earthquake, it did not move an amount sufficient to account for the total thrust component of at least 3.0–4.5 m (10–15 feet) which can be measured here.

Little Tujunga Canyon to Cassara Canyon. A well-defined surface break, with a vertical component of 25 cm (10 inches) and a left-lateral component of about 20 cm (8 inches), occurred on the first ridge top east of Little Tujunga Canyon. From here to Cassara Canyon, the trace is nearly continuous except where obscured by slope wash and old landslide debris on the hillside west of Cassara Canyon. The surface break is marked by numerous landslides triggered directly by movement of the Lakeview fault, which help to identify the fault and to expose the rocks involved.

The fault broke across the top of the ridge west of Cassara Canyon; however, it broke north of where it would be expected to break, judging by the mapped geology (121). Rocks of the Modelo Formation are in fault contact above rocks of the "thrust sequence" around the nose of the ridge 76 m (250 feet) south of the present breaks. Little, if any, movement occurred along this part of the fault contact, which can be followed along both sides of the hill to where it merges with the 1971 fault trace. From this ridge westward, the trace separates similar shale beds of the Modelo Formation and trends subparallel to the bedding. This contact appears to merge with parts of the inactive imbricate fault sequence discussed earlier (plate 2).

Minor breaks with the north side down occurred along bedding planes of the Modelo Formation in several places just north of the main surface fault but could not be followed more than a few tens of feet. These appear to be an expression of over-all thrusting forces, perhaps due to irregularities of the thrust plane or relaxation of the strain when the fault moved. Similar faults occurred north of the Sylmar fault segment

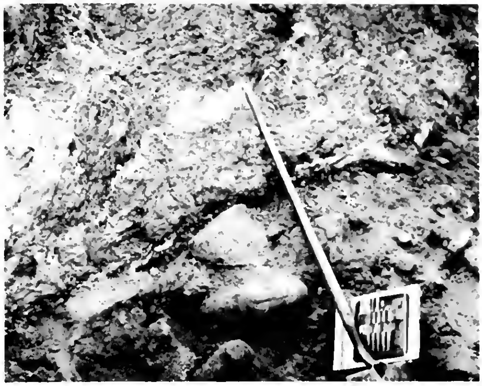


Photo 1. Fault scarp in gully west of Little Tujunga Canyon showing shale of the Modelo Formation in fault contact over alluvial cobble gravel. Locality (116), plate 3.

near the Highland Sanitarium (85) (Weber, this Bulletin) and elsewhere.

In the prominent saddle (123) north of the large hill between Little Tujunga Canyon and Cassara Canyon near the contact of the Modelo Formation and the Towsley/Pico Formation, large en echelon breaks trending northeast suggest a left-oblique-normal to normal sense of movement with the northwest side down (photo 2). Some ambiguity exists here between measured slip direction and calculated slip direction which ranges from approximately S. 88° W. to N. 45° W. These slip directions diverge toward both ends of the breaks. These faults cut bedrock of diverse textures as well as soil. They cross the ridge at an acute angle with the downslope side up on the east side of the ridge and the downslope side down on the west side of the ridge. They are nearly normal to bedding and appear to have a large lateral component of movement, all of which suggests a tectonic origin. A large extensional component of movement, the limited linear extent of the cracks, and their location near the heads of two large pre-existing landslides suggest a landslide origin. The writer favors the tectonic rather than landslide alternative, recognizing that a significant interrelationship between the two probably exists. Similar conditions may have influenced the formation of the other large landslides present along the contact between the Modelo Formation and the Towsley/Pico Formation.

Other breaks occur on the ridges north and west of the head of Cassara Canyon (124). Most of these displaced bedrock or thin soil but, unfortunately, have been obliterated by fire-break maintenance work. Parts of a few surface breaks are still visible adjacent to the firebreaks. The two with 8 cm (3 inches) of displacement (see plate 3) do not appear to be landslide related and might be related to the break to the south (123), but no continuity can be established. The one with 12 cm (4.7 inches) of displacement crosses the ridge at an angle to bedding, and the rest seem to be due to displacement along bedding planes. Those

Photo 2. View south toward large *en echelon* surface breaks across saddle and fire break northwest of Cassara Canyon. Left-oblique normal faulting is suggested. Locality (123), plate 3.

with 18, 10, and 4 cm (7, 4, and 1.5 inches) of displacement also parallel bedding; but their origin may be related to a landslide on the north side of the ridge (see plate 2), although they do not seem to parallel the landslide scarp.

Some movement occurred along the base of the hills on the east end of the Tujunga fault segment, east of Little Tujunga Canyon; but it was irregular and discontinuous. Breaks, roughly aligned and mostly compressional, are visible across several of the streets near the base of the hills. Breaks could not be found in the house lots between the streets except west of the end of Christy Avenue where a small mole track crossed two lawns. East of Christy Avenue, no evidence of faulting was found although some minor cracks did occur in a few driveways farther on.

Cassara Canyon to Oliver Canyon. The trace of the Lakeview fault between Cassara Canyon and Oliver Canyon is complex and difficult to delineate. Some portions have moved as imbricate plates. One area appears to be crossed by a series of tear faults, and the trace in other places is discontinuous or masked by slope wash.

The hillside east of Cassara Canyon is partly covered by thick slope wash or old landslide debris making it difficult to identify the main trace here. Discontinuous cracks and disturbed soil can be followed about half way up the hill where a good scarp is visible crossing a small ridge. Shale of the Modelo Formation is in fault contact above breccia or alluvium-breccia units here, but a short distance on up the hill the trace becomes diffused by branching or by forming a series of discontinuous northeast trending tension cracks. In places, these cracks are en echelon, indicating a large left-lateral component of movement and a vertical component with the southeast (downslope) side up. These tension cracks can be followed intermittently nearly to the top of the hill marked 1748 east of Cassara Canyon (125). They are believed, by the writer, to represent the surface expression of a zone of left-lateral tear faulting which crossed the hill here instead of breaking around its east side, where the fault contact between the Modelo Formation and the "thrust sequence" can be mapped. No movement occurred on this part of the fault contact because the rocks of the Modelo Formation which did move in the next canyon to the north (126) are not continuous across the gap of this canyon and hence could not push the rocks of the Modelo Formation on the east side of hill 1748 (see plate 2). Movement on this inferred tear fault has apparently been enough to cause a large slump fracture along the east-west ridge line of hill 1748. An old slide or patch of terrace gravel may be what has slumped; but exposures are poor, and the topographic expression is ambiguous.

A small landslide took place east of Cassara Canyon (122) between the first of August 1971 and September 14, 1971, downslope from and including previously mapped tension cracks, possibly related to the above-mentioned tear faulting. The slide is in shale of the Modelo Formation, but no apparent triggering mechanism could be determined. There had been no recent rain. Why the slide occurred six months after the earthquake is unknown, but it is important to realize that slides can happen long after an earthquake.

Movement took place between the alluvium-breccia unit and the older terrace gravel unit of the "thrust sequence" east of Cassara Canyon. The terrace gravel is thin here and overlies a wedge of sandstone and shale of the Modelo Formation. This movement may be related to the tear faulting inferred in this area or could be due to sympathetic movement accompanying that on the main thrust.

Distinct scarps are visible in both the west (126) and east branches (and on the hill separating these branches) of the canyon which parallels the power line between Cassara Canyon and Oliver Canyon. An 80-cm (31-inch) vertical component was measured in the alluvium of the west branch; and a 30-cm (12-inch) component in the alluvium of the east branch. In small slides along the trace, rocks of the Modelo Formation are well exposed and are in fault contact upon a thin breccia unit and the alluvium-breccia unit of the "thrust sequence".

The north-dipping fault trace, on the hillside east of this canyon, is truncated by south-dipping cracks along the west side of what the writer believes is a tectonic slide (127). This slide moved in previous earthquakes (displacing part of the thrust) and was reactivated in the 1971 earthquake. The trace which marks the scarp of this slide can be followed from here across several small ridges to the north-south ridge west of Oliver Canyon (129).

Vertical displacement as large as 160 cm (63 inches) was measured on the central part of this arcuate scarp which curves southward on its eastern end. In this vicinity, the scarp crosses a ridge and then runs parallel to it, displacing the ridge line relative to the hillside 60 cm (24 inches) downward on the west side (uphill side) of the scarp. Cracks and other surface breaks and detailed geologic relationships suggest that this slide has displaced a portion of the thrust fault which is now part of the slide, but is still identifiable and partly active. The thrust plane is severely warped within the bounds of the slide, but rocks of the Modelo Formation are still in fault contact with rocks of the "thrust sequence". Attitudes of the Modelo Formation in the slide are irregular and complicated by internal minor faulting but, in general, indicate a rotation of the slide mass. Movement along the displaced thrust plane, within the landslide mass, can be seen at several places around the base of the hill. In order for the thrust plane to be displaced, rocks of the "thrust sequence" under the fault must also be involved in the slide. However, since no recent movement of the rocks below the displaced thrust plane could be detected, it is likely that the lower parts of the slide may now be inactive and that present movement is taking place mostly on the displaced thrust plane.

The breaks outlining this slide are considered tectonic and are mapped as fault breaks because they appear to be the direct result of movement on the thrust where it intersects the slide plane. A road cut on the west margin of the slide exposes conclusive evidence for repeated, presumably tectonic, movement on this slide plane and/or fault. The present displacement, which is less than 50 cm (20 inches) here, occurred along an old break which previously displaced shale of the Modelo Formation at least 1½–2 m (5–6½ feet) down on the south. The scarp formed by this former break has loose, jumbled, unbedded sand and shale debris deposited downslope from it on top of the displaced rocks of the Modelo Formation. The cracks formed in this earthquake extend on down the face of the cut and displace debris and sand which fill the older crack. None of this debris is fresh enough to have been deposited since the earthquake. The east margin of the slide (129) appears to displace the thrust plane, and a lateral component of movement consistent with this concept can be measured on a ridge top here.

Along the hillside west of Oliver Canyon, the fault is well exposed by small slides (130) (photo 3), and a continuous trace is visible. A scarp with a 153-cm (5-foot) vertical component of displacement can be mea-

Photo 3. Lakeview fault trace along hillside west of Oliver Canyon marked by small slides. White layer in largest slide is fault breccia. Note boulder gravel of "thrust sequence" at base of hill and extending on up the canyon.

sured where the fault crosses the alluvium of the canyon. The road in the canyon bottom was displaced, and a barn on the scarp was badly damaged (photo 4). The fault dips about 30° N. here; and its contact with fluvial gravel, dipping about 10° N., is visible in a slide on the west side of the canyon.

Oliver Canyon to Schwartz Canyon. Between Oliver Canyon and Schwartz Canyon, the fault is generally a single easily followed mole-track scarp except where landslides have exposed the rocks involved (132). It is a less prominent trace in this stretch, compared to some other areas, but is still distinct. Where it traverses part of the hillside east of Oliver Canyon, it is either hidden by slope wash or did not move enough to form surface breaks. This is also true a short distance along the hillside west of Schwartz Canyon, close to where the trace crosses the alluvium.

The dip of the fault in this section changes from about 30° N. in Oliver Canyon to about 10° S. near the distal end of the lobate trace (131). This warp of the fault plane, discussed earlier, appears to be a reflection of warping in the underlying rocks. It may also be partly due to the large horizontal component of thrusting here; the rocks of the upper plates have been pushed down the front of the hill faster than erosion can remove them.

The ridge between Oliver and Schwartz Canyons was faulted and severely cracked. Large tension cracks formed over a broad area of the hilltop, part of which has been cultivated. Bedrock can be seen in many of the open cracks; and a soil layer, as much as 50 cm (1.6 feet) thick, has been exposed. The area is bounded on the east and west sides by long continuous northeast-trending cracks considered by the writer to be fault breaks. These breaks are displaced an average of 50 cm (1.6 feet) vertically upward on their downhill sides. The fault on the west side, which is 12 m (40 feet) below the crest of the ridge along its central part, ascends the ridge at either end. This fault is superposed on a pre-existing bench along the hillside which was presumably formed by previous faulting in the same place and with the same sense of movement (D. H. Radbruch, personal communication). The fault on the east side cuts across the head of a gully transecting rocks of the Modelo Formation normal to the strike of the bedding. The area between these two faults is laced with both small and large cracks, many of which may also be faults since they extend into the bedrock. They have been mapped as cracks because they appear to be caused by lateral spreading of the whole area between the bounding faults. Desiccation cracks in the cultivated field appear to have expanded with fresh breakage along their edges. Some of the openings appear to have widened farther than normal, which also suggests spreading.

Large older landslides occur on both sides of the ridge, north of the badly cracked area; but none was reactivated in the earthquake. A few cracks adjacent to the slide scarp on the west side of the hill may be related to consolidation of the material in the slide, but no significant movement occurred. A medium-sized rotational slide, unlike the "skin slides" which occur along the fault, formed above the Lakeview fault trace on the west side of Schwartz Canyon. The toe of this slide coincides with the fault trace, suggesting that it may have been triggered by movement on the fault as well as by shaking. This may be a reactivated older slide, but it is now difficult to decide this without pre-earthquake data.

Schwartz Canyon to Lakeview Terrace Sanitarium. The fault trace in the alluvium of Schwartz Canyon is distinct and has a vertical component of about 30 cm (1 foot), and the scarp is typically expressed as a mole track (photo 5). Along the east side of Schwartz

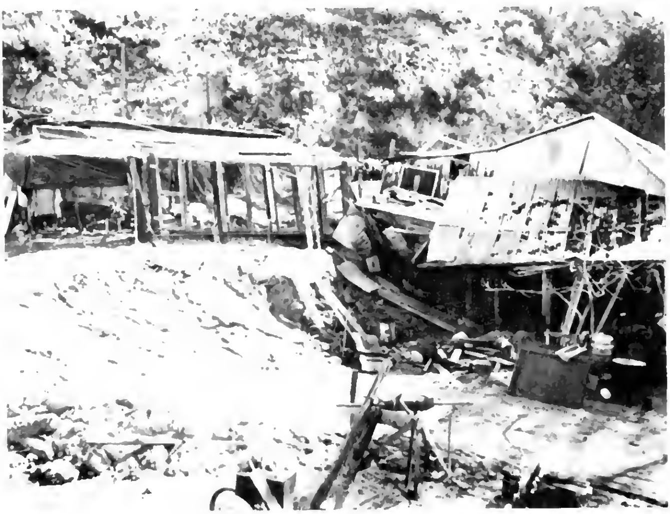


Photo 4. Fault scarp and damaged barn in Oliver Canyon. The bird pens to the left were nearly level with the floor of the barn before the earthquake.

Photo 5. Fault scarp in the alluvium of Schwartz Canyon. Stereoscopic view west; note hat for scale.

Canyon, it is difficult to follow the scarp. Midway along the hillside, it is well exposed where it forms the sole of a landslide which extends above the trace nearly to the top of the ridge. The fault is distinct where it crosses the ridge east of Schwartz Canyon, and it can be traced with confidence as far as the small canyon east of the Lakeview Terrace Sanitarium through a series of small landslides which expose the fault contact.

Landslides along this portion of the fault trace deserve special mention because they are much more common here and, locally, are nearly continuous along the trace. All are atypicial "skin slides" directly related to fault movement. The contact between the Modelo Formation and the alluvium-breccia and/or the breccia unit of the "thrust sequence" is well exposed where the slides occurred. The breccia unit is very thin and is apparently absent in some places. The amount of movement on the thrust does not seem to be any greater here than elsewhere, but the steepness of the slopes may be a factor which controlled the density of the slides. Beds of the mixed alluvium-breccia unit are commonly in direct fault contact with rocks of the Modelo Formation here. The mixed alluvium-breccia unit becomes thinner toward the east.

A second line of imbricate, weaker faulting, mentioned earlier, can be traced along the top of the older terrace gravel unit of the "thrust sequence" around the nose of the two hills between Schwartz Canyon and the Lakeview Terrace Sanitarium (133). The scarp here is less distinct than that of the main fault, but its expression is nearly continuous. Small landslides occur very close to the fault trace both above and below it but do not form a consistent pattern along the trace as do those along the main fault.

The soil is severely cracked on the slopes above, in between, and below the main and lesser traces of the thrusting. Patches of shattered soil are abundant, and some of the cracks have a "tipped-outward" sense of movement on them (photo 6). The soil cover appears to have been shaken so severely that, instead of slumping on the hillside as would be expected of loose material and rotating so that the slope of the original surface is less steep ("tipped-inward"), blocks of soil seem to have been flung outward from the hillside and to have rotated so that the slope of the original surface became steeper ("tipped-outward"). This

Photo 6. Severely cracked soil showing "tipped-outward" rotation of blocks in the proximity of houses north of Foothill Boulevard, east of Schwartz Canyon.

phenomenon was also noticed in the San Francisco earthquake of 1906. Crandall (Lawson, 1908, p. 253) described cracks several hundred feet long, a mile east of the main trace of the San Andreas fault, with several inches of downthrow on the uphill side. Much of the soil and perhaps some of the underlying rock has been loosened in this way. During periods of heavy rain, sufficient water may collect in these cracks to cause serious sliding or mudflow problems in the area. This possibility, combined with the fact that houses have been built close to the base of the hills here, should be cause for serious concern each time it rains and particularly during heavy rains (Morton, this Bulletin).

Lakeview Terrace Sanitarium to Bill Lane Camp. From the small canyon east of the Lakeview Terrace Sanitarium, the fault trace is poorly defined or hidden until it enters the alluvium of Tujunga Valley. It appears to cross a terrace deposit east of this small canyon, but the evidence is equivocal where only very small mole tracks can be seen on the surface of the terrace.

The fault scarps in the coarse bouldery alluvium of Tujunga Valley trend subparallel to the current stream channel, crossing it in several places and causing ponding of sediments or forming short reaches with a sharply steepened gradient. The scarps cut various kinds of alluvium, such as soft sand deposits (photo 7) (135), gravel deposits (photo 8) (136), boulderly flood channels, areas of sparse soil accumulation with light vegetation, bulldozer cuts, bridle trails, and islands of flood debris. Various components of movement were measured; vertical components range from 20 to 130 cm (8–51 inches) and left-lateral components range from 20 to 100 cm (8–39 inches). Some evidence was found suggesting a moderate compressional component. This may account for the commonly sharp, well-defined trace and for the steepness of the scarp face, close to the angle of repose for loose, dry, granular material. Little cracking could be found except very close to the trace (photo 9) (135), which contrasts sharply with the area adjacent to the fault trace in the hills to the west.

The fault trace in the alluvium of Tujunga Valley was distinct and easily followed over most of its length shortly after the earthquake. Very soon after it formed, it was modified by flowing water or buried by sediment where it crossed the present stream channel. In the rest of the alluvium of the flood plain, the scarps were still well defined a year after being formed although wind and rain have modified them slightly and horse and motorcycle traffic has nearly obliterated some small sections. The linearity of the trace and an ambiguous exposure of a jumbled but partly aligned zone of cobbles, dipping approximately 45° N. in trench 6, suggests a steeper dip on this part of the fault than farther west along the Lakeview fault.

Very rough estimates of slip were made at several points where a strong left-lateral component, as well as a vertical component, could be measured on features displaced by the fault and crossing it at an acute angle; suggested dips are greater than 45° N. Near the mouth of Ebey Canyon, a dip of 60° N. was measured on a fresh scarp at the base of the bluff which had at least 100 cm (39 inches) of reverse dip-slip movement on it (photo 10) (137). Slickensides on this scarp between rocks of the Towsley/Pico Formation and the alluvium of Tujunga Valley formed in this earthquake. Older slickensides would presumably have been obliterated when the alluvium was being deposited. The plunge of the slickensides is nearly coincident with the dip, indicating a slip direction close to S. 30° W.

Photo 7. View north of fault scarp in soft sand of Tujunga Valley. Scale graduated in centimeters and inches. Locality (135), plate 3.

Photo 8. View west of fault scarp in sand and gravel of Tujunga Valley. Note landslides along cliff face in right background. Locality (136), plate 3.

Photo 9. View west of fault scarp in the alluvium of Tujunga Valley. Note the limited width of broken soil, sand, and gravel. Hat for scale. Locality (135), plate 3.

A slight rotation of the slickensides was visible (photo 11) (137), suggesting a left-lateral component of motion as the fault started to move but which rapidly changed to dip-slip movement. Three months after the earthquake, this evidence had been nearly obliterated by caving of the cliff face (photo 12) (137).

The Lakeview fault scarp crosses Oro Vista Avenue and displaces the road 100 cm (39 inches) left laterally and 40 cm (16 inches) vertically with the north side up. East of here, the fault trace swings from an east trend to a northeast trend and disappears in an area covered by fill. It reappears along the north side of the hill, labeled Bill Lane Camp on the map, as a scarp in bedrock separating rocks of the Towsley/Pico Formation and rocks of the Modelo Formation (138). The fault plane dips 65° N; the north or downhill

Photo 10. Fault scarp near the mouth of Ebey Canyon. Taken on March 2, 1971; clipboard for scale. Compare with photo 12. Locality (137), plate 3.

Photo 11. Detail of fault scarp near the mouth of Ebey Canyon. Stereoscopic view showing slickensides which coincide with the dip of the fault plane. Scale graduated in centimeters and inches. Locality (137), plate 3.

side has been uplifted about 30 cm (12 inches). No evidence for lateral movement could be found here. A short distance farther northeast, however, a fence which crosses an obscure part of the trace at an acute angle has been offset 15 cm (6 inches) left laterally. Because of the angle of intersection of the fault trace and the fence, the amount of movement on the fault required to form that much offset on the fence would be about 45 cm (18 inches) left lateral. No measurable vertical component could be found, and the fault could not be followed farther than this. The alluvium of Big Tujunga Canyon between here and County Camp Fifteen (141) was searched carefully, but no unambiguous evidence for faulting was found.

At Bill Lane Camp, a line of cracks or small faults which break bedrock trend up and across the hill

Photo 12. Fault scarp near the mouth of Ebey Canyon. Taken on May 9, 1971; clipboard for scale. Locality (137), plate 3.

southwestward from the main fault trace. These are mapped as cracks because they traverse the slope above and may be related to the large landslide seen on this hill. This slide was not activated by the earthquake, but much of the loose material in it was disrupted.

In line with these cracks and at the south base of the hill, a small fault scarp was detected where shale of the Modelo Formation had been thrust 25 cm (10 inches) over a mixed unit of alluvium and breccia very similar to the alluvium-breccia unit under the Lakeview fault. This alluvium-breccia mixture overlies coarse, bouldery older alluvium which does not resemble the older terrace gravel of the "thrust sequence" except for being fluvial in origin. It is nearly monolithologic alluvium composed of boulders and gravel much coarser grained and with many more clasts of diorite than the older terrace gravel to the west or the gravel of Tujunga Valley. It is probably an old terrace deposit and has been mapped as older terrace gravel.

Other Faults

Minor faults, with vertical displacements from 5 to 35 cm (2–14 inches) but of limited length, were found at scattered locations north of the Lakeview fault area. Because this area was covered only in reconnaissance, it is safe to assume that a more thorough study might reveal additional faulting, such as that found in the area north of the Tujunga fault (Barrows, this Bulletin, and plate 2).

On a spur of Yerba Buena Ridge (142), several faults and associated small cracks occurred in bedrock of the basement complex. They cross the ridge crest and have vertical displacements of 5–15 cm (2–6 inches) with the south or downslope side up where they traverse the hillsides. No lithologic controls could be found to explain their origin, and they do not appear to be related to landsliding. They resemble similar faults and cracks on Kagel Mountain (49) (see Barrows, this Bulletin).

A fault which occurs partly in terrace deposits and partly in bedrock in the upper reaches of Doane Canyon moved upward on the north side 35 cm (14 inches). This fault appears to separate basalt of the Topanga Formation from rocks of the Modelo Formation near its eastern end but does not correspond closely with the geology compiled for the map in this area. It is evident from the geologic map (plate 2) that this break is close to, but not on, one of the mapped traces of the Sunland fault. Sharp (1934) shows a fault in this area corresponding more closely with this break than the geology compiled for plate 2.

Minor bedding-plane faults with less than 15 cm (6 inches) of reverse movement occur in the area west of Big Tujunga Canyon (139) and near the mouth of Ebey Canyon. None of these faults appears to be very long but, during the earthquake, would have seriously damaged any structures built over them.

Other Surface Effects

Cracks not related to faulting. Cracking, which is ubiquitous along the main fault traces, is usually but not always restricted to the upper plate and in many places extends upslope for many tens of feet. Because of the scale of plate 3, most of these minor cracks cannot be shown. The areas of significant cracking have been discussed under the detailed descriptions of the fault breaks.

The natural cutbanks of streams, the eroded edges of terrace deposits, and the steep edges of some ridges showed many cracks and slumps. Many of these effects were not extensive enough to be shown in plate 3. Since they are commonly related to landslides or rockfalls, their density should be evident.

Some cracks crossed Mt. Gleason Avenue, just south of County Camp Fifteen (141). These cracks, together with cracks in the alluvium along the west side of the road (140), which also broke a water line in several places, suggest possible fault movement; but the evidence is ambiguous.

Many prominent cracks and other effects are visible in the terrace deposits and the soil along the Sunland fault west of Big Tujunga Canyon (139). These appear to be due mostly to severe shaking. The bases of many of the isolated patches of poorly consolidated terrace gravel appear to have moved enough to cause intermittent cracking in the soil at the contact with the underlying Tertiary rocks. Large boulders are very abundant near the base of these terrace deposits and may have acted as "bearings," amplifying the shaking effects.

Shattered ridge tops. A very unusual surface effect, largely restricted to ridge tops, was widespread as a result of this earthquake. The soil on literally hundreds of ridge tops throughout the epicentral area was completely shattered, presumably by severe shaking. Cobble-size clods of dry soil appear to have been broken loose and tossed about, in some places being partially disintegrated and occasionally being turned completely upside down.

This phenomenon has been called shattered earth (Nason, 1971, p. 97), shattered ridge tops (Kahle and others, 1971; Barrows and others, 1971), and shattered ridges (Evans, this Bulletin). This sort of thing has apparently happened in other earthquakes but has never been reported over so large an area (plate 3). Others have used the terms "exploded ridge" and "plowed ground" to describe these features. Davis and West (this Bulletin) discuss the effects of topography on ground motion.

Oldham (1899, p. 10), in his report on the great Indian earthquake of 1897, quoted a report by A. A. Howell which deserves repeating: ". . . where the soil is sandy and the surface fairly level, the ground looks as if a steam plough had passed over it, tearing up the turf and throwing the clods in every direction, some up hill and some down, and in many cases turning the sods completely over, so that only the roots of the grass are visible."

R. Crandall (in Lawson, 1908, p. 253), in describing the effects of the 1906 earthquake on Cahill's Ridge south of San Francisco said: "In an area of limestone, a small patch some 30 feet in diameter was torn up as tho it had been plowed and harrowed, and no large pieces of sod were left intact." He also noticed the "tipped-outward" appearance of peripheral cracks (commonly associated with shattered ridge tops in the San Fernando earthquake) and says: "There was a slight downthrow on the uphill side to be noticed in some of these cracks, which eliminated the possibility that they were cracks preparatory to landsliding." Bonilla, in describing the effects of the San Francisco earthquakes of March, 1957 (1959, photo 1), shows a picture of very similar cracks and describes them: ". . . as though an explosion had been set off beneath it . . ." These descriptions could as well be applied to the shattered ridge tops caused by the San Fernando earthquake.

The shattering effect seen in the San Fernando earthquake appears to be restricted to ridge tops of various widths and shapes, albeit relatively narrow, suggesting some topographic control; but, in many places, only short stretches of long uniform ridges were affected. The trend of the ridges which shattered seems to be random. Lithologic controls appear to be a strong factor also (Barrows, this Bulletin). In one place, near San Fernando pass, shattering was seen with no difference in appearance in both soil cover and adjacent bedrock. In the area between Little Tujunga Canyon and Big Tujunga Canyon, most of the shattering seen was restricted to unconsolidated terrace gravel, to soft sandstone and shale beds in the upper part of the Towsley/Pico Formation, or to a narrow zone in the Saugus Formation about 460 m (1500 feet) south of the Sunland fault. Shattered ridge tops were also common near the surface faults.

Landslides and rockfalls. Morton (this Bulletin) has described the character and distribution of landslides and rockfalls in the whole epicentral tract (shown in red on plate 3). The landslides along the Lakeview fault have been described. There seems to be a local abundance of landslides and rockfalls in the area north of and adjacent to the Sunland fault, particularly near its eastern end. This may represent more severe shaking in the rocks of the upper plate of the Sunland fault, perhaps in response to slight movement on it or to the more broken character common to rocks in the upper plate of a thrust.

Fill failure. Failure in artificial fill was widespread. Fills, particularly along secondary and fire access roads or where oversteepened by erosion, commonly were affected by the earthquake. Roadcuts commonly failed along their upper edges. Controlled artificial fill fared somewhat better, but it was not uncommon to see cracking and slumping of the angular edges. Structures set back far enough from the edge were unaffected in some cases. Fills in other areas responded poorly (Weber; Barrows; Saul; this Bulletin). This kind of cracking is not indicated on plate 3 because, in this study, it was not possible to evaluate the varying degrees of engineering control employed.

CONCLUSIONS

Movement, mainly on the San Fernando fault zone, caused the February 9 earthquake. Prominent scarps were formed which made it possible to delineate several formerly unrecognized faults. The displacement on the Lakeview fault segment was as large as that on the other segments of the San Fernando fault zone; but, except for the scarps in Tujunga Valley, the trace was much less evident. Its continuity was not recognized for a time because the evidence was hidden by a profusion of landslides. Detailed mapping revealed a pattern of displacement consistent with the geological units and their relationships under the fault. A distinctive sequence of rocks is critical to the interpretation of active thrusting and, along with the heave measured on the fault, supplies evidence that the fault probably has been active for the last 60,000 plus years.

The Lakeview fault is imbricate and consists of several planes between Kagel Canyon and Cassara

Canyon. This evidence suggests that connected, anastomosing thrust faults, as commonly mapped, may be an oversimplification.

Surface faulting is confined to a zone ranging from about 3 m (10 feet) to as wide as 475 m (1550 feet) because of the sinuous nature of the gently dipping trace. Significant but secondary faulting also occurred across a zone 3 to 5 km (2 to 3 miles) wide north of the main trace.

With enough detailed geologic mapping, even without such aids as trenching and drilling, there is a very good chance that much of the Lakeview fault segment could have been identified before the earthquake. It is also very likely that no amount of mapping, drilling, and trenching could have located the places where secondary faulting took place. The other surface effects, particularly shattered ridge tops and landslides, were even more widespread and would be even more difficult to predict. If the trace of a fault is well known, it can be avoided; but secondary faulting and the other surface effects can be just as devastating to any structure located where they occur. This has serious implications for any attempts to zone similar areas for development or in attempting to evaluate any area for seismic hazard.

The writer has attempted to demonstrate the value of geologic mapping in delineating an active fault. It is always helpful, of course, to know that a fault is active before one attempts to prove it. Along the Lakeview fault, the geologic evidence for late Holocene thrusting seems compelling enough to have raised the suspicion that the Lakeview fault was capable of renewed movement, even without the proof of a magnitude 6.4 earthquake accompanied by major surface faulting.

ACKNOWLEDGMENTS

The willing cooperation and assistance of many residents in the area, giving both time and information, is gratefully acknowledged. Gordon B. Oakeshott graciously lent his very valuable field maps (1:24,000 scale) on which he had originally mapped the geology for his bulletin on the San Fernando quadrangle (1958). Valuable discussions in the field with many staff members of the California Division of Mines and Geology, with Dorothy Radbruch of the U. S. Geological Survey, and with Richard Crook, Jr., and Mark H. McKeown of the Metropolitan Water District of Southern California were very helpful. Ed Heath and Bob Dickey of F. Beach Leighton and Associates assisted in logging the trenches dug by the Division in the area. Examination of the trenches dug by the U. S. Geological Survey, at the invitation of M. G. Bonilla, proved very useful. State and local agencies cooperated fully.

Geologic Effects of the San Fernando Earthquake in the Newhall-Saugus-Valencia-Solemint Area

by James R. Evans [1]

A brief survey was made of geologic effects and their relation to major damage in the Newhall-Saugus-Valencia-Solemint area (see figure 1) in the first seven days after the San Fernando earthquake of February 9, 1971. All photos used in this report were taken during that period.

Most earthquake damage can be related in a broad way to the four geologic environments discussed in this article. In order of decreasing economic significance, these are:

1) Ground cracking and shaking of the upper Miocene and lower Pliocene Towsley Formation, the Pliocene Pico Formation, and the Pliocene Sunshine Ranch Member of the Saugus Formation.

2) Ground shaking of graded alluvial covers on Quaternary terrace deposits, Pliocene and lower Pleistocene Saugus Formation, and upper Miocene Mint Canyon Formation.

3) Ground shaking of pre-Cretaceous granitic, anorthositic, and gabbroic rocks in the San Gabriel Mountains.

4) Ground shaking and cracking in the Saugus Formation.

GROUND CRACKING AND SHAKING IN PLIOCENE FORMATIONS

Damage in this geologic environment was centered in the San Fernando Pass-Grapevine Canyon area north of the Van Norman Reservoirs. The importance of the area to greater Los Angeles cannot be overemphasized. Not only does the Los Angeles City Aqueduct system pass though here, but there are distribution tunnels for the California Water Project (not yet in operation) and the Golden State Freeway with overpasses near the intersection of the Sierra Highway (Antelope Valley Freeway) and the Foothill Freeway. In addition, the Southern Pacific Railroad line and tunnel pass beneath the freeway overpass network.

All of these major structures were damaged during the earthquake. Water transport was stopped in the Los Angeles City system because of breaks and cracks in lines. The very high Antelope Valley Freeway overpass collapsed onto the Golden State Freeway about 100 feet (30 m) below and then onto the railroad tracks just south of the railroad tunnel entrance (photo 1 and California Division of Highways [this Bulletin]). Rail service was out for four days, and trains were rerouted. Normal traffic flow on the Golden State Freeway was interrupted for a few months, until temporary freeway structures could be completed. Freeway bridge and overpass structures had not been rebuilt as of January 1972.

[1] California Division of Mines and Geology, Sacramento.

The types of geologic failures found in this area are:

1) Slope failure by shaking:
   a. down the dip of beds at moderate slope angles.
   b. across the dip of beds at steep angles.
   c. debris falls and dry debris flows on steep slopes.

2) Ground cracking in soils and rocks, locally resulting in shattered ground on steep, narrow ridges underlain by steeply dipping weak rocks.

3) Ground rupture (faulting?) with displacement of surface rocks.

4) Cracking in roads, road fills, and fills adjacent to the Los Angeles City Aqueduct and Golden State Freeway structures.

Slope Failure

The most prominent earthquake-triggered landslide in the area was along a ridge about 2000 feet (600 m) south of the Sierra Highway intersection with the Golden State Freeway. It is adjacent to a 100-foot-high (30 m) cut on the west side of the existing freeway system and about 125 feet (38 m) above it (photo 2).

In plan, the slide mass is about 750 feet (227 m) long in a northeast direction and about 450 feet (136 m) across. The mass extends down slope about 200 feet (60 m) from the ridge top. Because of the irregular failure-surface of the slide, it is difficult to determine thickness of the mass without trenching or drilling. If an average thickness figure of 24 feet is used, there were about 900,000 cubic feet (225,000 m^3) of material involved in the failure. This is probably a minimum figure.

Strong vibration caused water-laden beds in the Towsley Formation to fail along and across bedding planes and to lurch out and down slope through the (2:1) cut. The Towsley Formation here is composed of interbedded porous brownish sandy silt and grayish friable fine-grained sandstone. Beds strike northwest and dip about 20° northeast. These rocks are inherently very weak, particularly when saturated with water; and much support was removed when the freeway cut was made. Consequently, rocks in the upper part of the slope could not stand under the intense shaking. Near the ridge top, blocks of rocks 10 to 15 feet (3 to 4.5 m) across and 10 feet (3 m) or higher broke apart and slid away from each other (photo 3).

The lower part of the mass apparently broke away from the slope across bedding planes, lurched outward through the cuts, and virtually crumbled and "flowed" down slope.

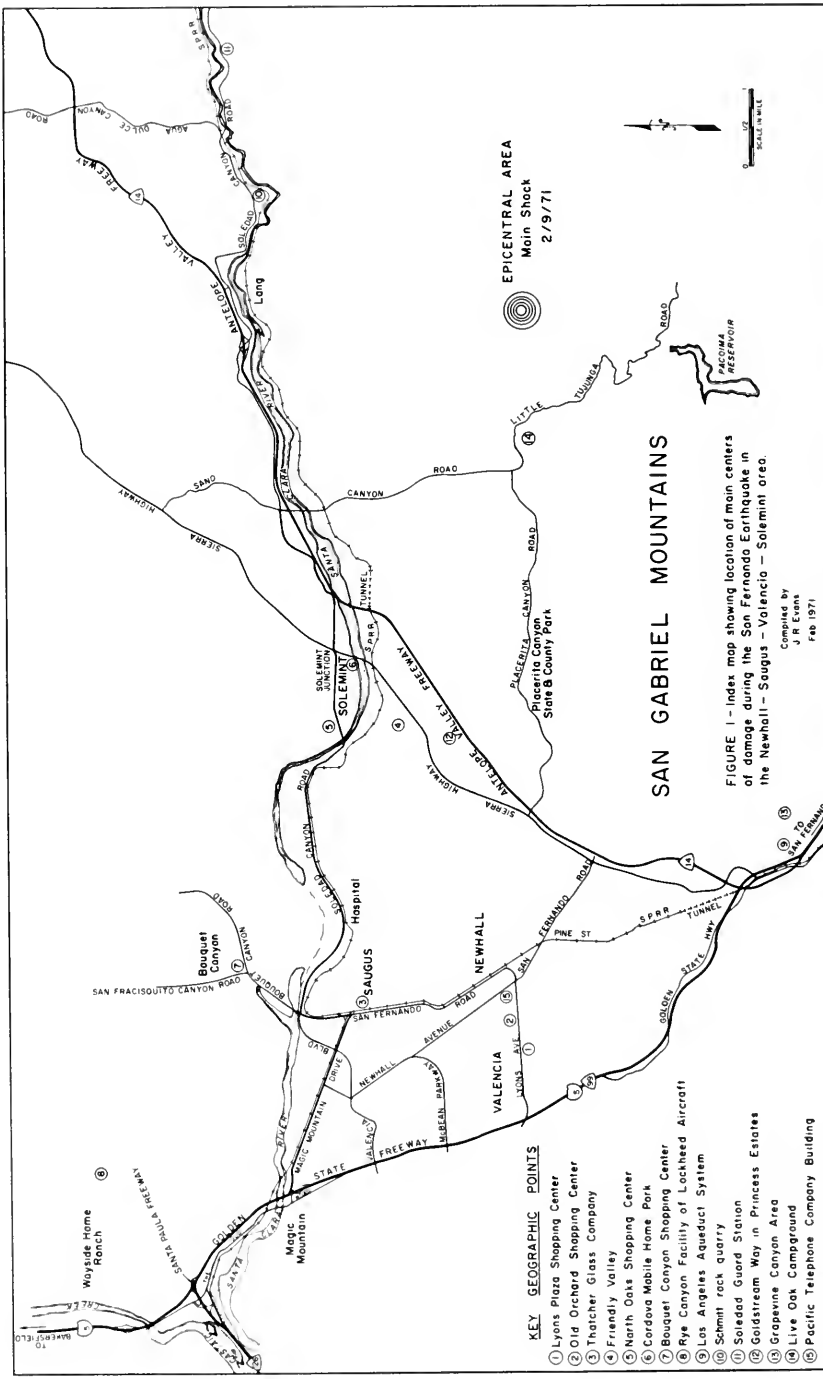


Figure 1. Index map showing location of main centers of damage during the San Fernando earthquake in the Newhall-Saugus-Valencia-Solemint area.

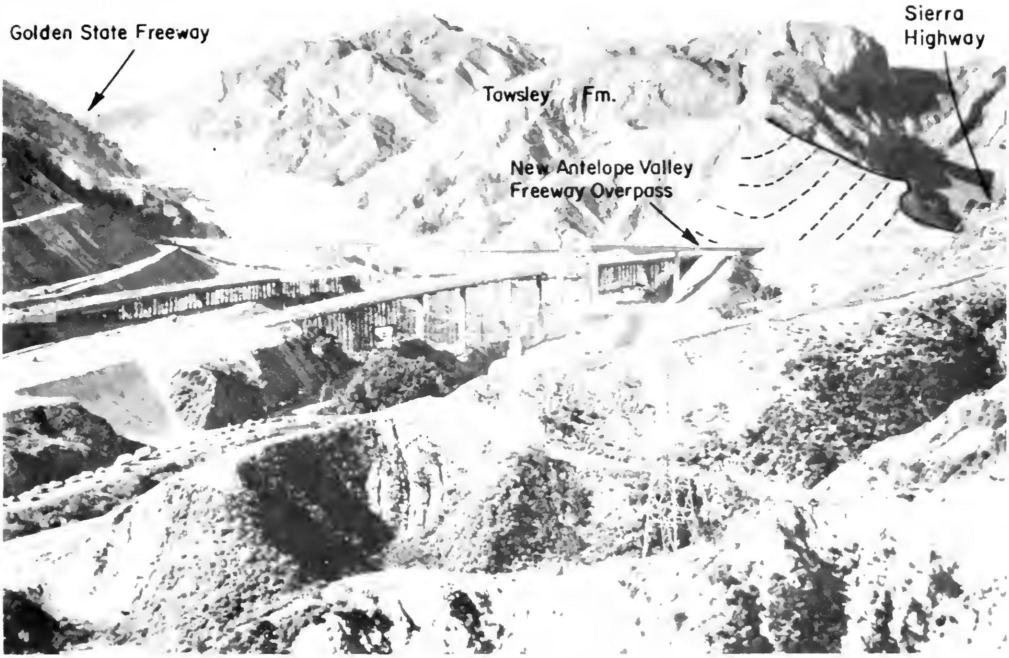


Photo 1. Collapsed overpass of the Antelope Valley Freeway, just north of the Sierra Highway intersection with the Golden State Freeway. Beds of the Towsley Formation are strongly deformed in this area, and a tightly folded syncline is well exposed in the adjacent cut. View is north.

On the east side of the Golden State Freeway, just south of its intersection with the Sierra Highway, another mass of Towsley Formation failed through a 100-foot-high (30 m) cut of 1½:1 ratio (photo 4). This failure was in water-laden, highly fractured siltstone and sandstone similar to the beds described above; however, there were significant differences between these failures. In this second slide, the cut slope was steeper and the rock mass was only roughly half as large in plan view; however, because of the arcuate nature of the slide plane, it had a greater average thickness. Possibly the cubic feet were nearly the same, but drilling would be needed to confirm this. The second slide mass lurched forward but did not come down slope more than several yards. This mass failed across the strike of beds which trend east-northeast and dip about 60° north, and the long axis of the mass trended west-southwest. The toe of the mass largely remained buttressed by pre-existing fill in a canyon adjacent to the south-southeast. The toe is only about 50 feet (15 m) from the freeway; in January 1972, this mass still posed a threat to traffic should it fail after heavy rains or during an earthquake.

As of January 1972, neither of these two slide areas had been corrected. Extensive grading, resulting in a lower angle for the cut faces, will be necessary for correction.

A large debris-fall occurred on the hill just west of the portal of the Los Angeles City Aqueduct. Here, a very steep, natural slope existed on fractured, west-trending, steeply dipping tan siltstone and sandstone of the Pico Formation. The water-saturated weak rocks could not withstand the strong shaking on the steep slope. Rocks broke into pieces a fraction of an inch to as much as several feet across and fell or rolled downslope (photo 5). Although this was the largest such failure observed in this area, other small debris falls and dry flows were very common along steep slopes, particularly along cuts on the Grapevine Canyon road and in the Magazine Canyon area.

Ground Cracking

Two ridges exhibited the peculiarly cracked ground referred to here as shattered ridges. One was in the Towsley Formation in the NW¼ of Section 19 under transmission-line towers of the Los Angeles

Photo 2. Earthquake-triggered landslide along the unfinished southbound lane of the Golden State Freeway, San Fernando Pass area. Weak, fine-grained, clastic beds in the Towsley Formation lurched parallel to the strike of beds and slid down along the dip (see photo 3). Failure took place during first strong shaking. Flat area in left background is a Los Angeles County sanitary land-fill. View is southwest. *Photo courtesy of the Grading Section of the Los Angeles Department of Building and Safety.*

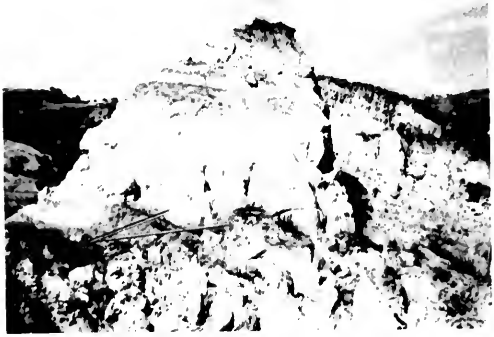


Photo 3. Breakaway scarps in the landslide shown in photo 2. View is north from the top of the ridge.

Department of Water and Power (3/1) and Southern California Edison Company. The towers are roughly 100 feet (30 m) apart on a narrow, steep northeast-trending ridge extending out from the main mountain mass. A northwest-trending and steeply dipping fault separates the ridge from the mountain mass, which is composed largely of pre-Cretaceous biotite schist and diorite gneiss. Thin beds of fractured siltstone, sandstone, and shale in the Towsley Formation strike northeast parallel to the long narrow ridge and dip about 80° to the northwest. The steeply inclined weak beds failed under the strong earthquake motion. Crack swarms and intensely broken zones were developed in the top few feet of weathered bedrock and soil. Cracks extend about 200 feet (60 m) along the ridge under both towers. Several footings and embankment supports for the towers were undermined or failed, but fortunately the towers did not fall (photo 6).

Photo 4. Earthquake-triggered landslide in a steep cut at the intersection of Sierra Highway with Golden State Freeway, San Fernando Pass area. Weak, fine-grained, clastic beds in the Towsley Formation have failed across their strike. Part of the toe of the slide was buttressed by a previous fill in the canyon to the south. View is northeast. *Photo courtesy of the Grading Section of the Los Angeles Department of Building and Safety.*

Another shattered ridge (Hill 1863, San Fernando 7½′ quadrangle) was just west of the Los Angeles City Aqueduct and adjacent to the access road to the tank that feeds the air-splasher drain. Geologic conditions here are similar to those described above. The ridge is elongate in a westerly direction, parallel to the strike of soil-mantled siltstone beds in the Pico Formation. Beds dip very steeply north. Cracks and broken ground were visible for about 300 feet (90 m) along the ridge.

The access road to the tank area near the ridge showed cracks in the asphalt, mostly at a high angle to the center line. Road fill also cracked but mostly parellel to the road. Rock falls from steep road cuts and natural slopes were common in the fractured and fine-grained rocks of the Pico Formation. The asphalt-covered cut at the west end of Hill 1863 failed locally. Extensive cracking in the asphalt took place in the tank area. Sinking occurred locally on asphalt-covered fill over the pipeline leading into the tank.

An area of deformation was noted in clastic rocks of the Pico Formation near the air-splasher drain. About mid-way down the hill and about 20 feet (6 m) east of the drain were two surface cracks and an area of shattered ground. Both cracks were well exposed in a small cliff. The crack to the west trended north parallel to the drain, was nearly vertical, and extended down at least 3 feet (1 m). About 3 feet (1 m) west, there was another, larger, crack. This crack trended a little east of north, and near the ground surface rocks were pulled apart several inches along it. It is exposed for a few tens of feet (several meters) along the strike and in the cliff face for about 10 feet (3 m) of depth at right angles to the dip. Near the surface, the crack dips 55° east, but within a distance of only several feet it shallows in a gentle arc to about 30° east (photo 7). A few feet to the

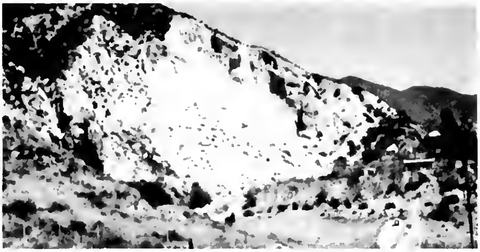


Photo 5. Debris fall on steep slopes of the Pico Formation near the Los Angeles Aqueduct, San Fernando Pass area. View is east from the Golden State Freeway.

Photo 6. Shattered soil and weathered zone on steep, north-dipping beds of the Towsley Formation, San Fernando Pass area. View is southwest toward Southern California Edison Company transmission-line tower 3/1.

Photo 7. Ground cracks in sandstone of the Pico Formation adjacent to the Los Angeles Aqueduct. View is north.

south is a zone of shattered ground about 20 feet (6 m) wide and 100 feet (30 m) long parallel to the drain. Both the cracks and shattered ground have resulted from strong ground shaking in fractured weak rocks.

Further down slope, in a flattish area near where the drain and pipeline pass under the Golden State Freeway, a different type of damage occurred. This area is underlain by siltstones of the Sunshine Ranch Member of the Saugus Formation, with a local thin alluvial cover. Drain walls were cracked and broken near the underpass, as were water pipes. The roof of the underpass failed, dropping down about a foot and a half (half a meter) on the east and breaking one of eight attached electric lines. An air gap was visible against the west wall of the underpass where shaking had caused the wall to separate from the adjacent fill. The floor of the underpass adjacent to the wall was cracked for about 150 feet (45 m) from the northeast entrance.

About 500 feet (150 m) north of the underpass a 200-foot-long (60 m) crack, as much as 2 inches (5 cm) wide, opened up parallel to the drain. The crack was in fill and about 2 feet (2/3 m) from the side wall of the drain. In the same area are two culverts which carry water from the older pipeline system to the new one. Cracks developed in the fill adjacent to and parallel with the culvert walls.

Minor ground cracks in the Towsley Formation are well exposed in a 25-foot (8 m) cut along the access road for the Saugus pipeline (Pipeline Station 777+55.05), southwest of Hill 1879 (San Fernando 7½′ quadrangle) and east of the Sierra Highway intersection with the Golden State Freeway. Beds exposed in the cut are much fractured, friable, brownish siltstone and light gray, fine-grained sandstone. They strike east-northeast and dip 60° north-northwest. A 3-foot (1 m) high cut was made at right angles to the road cut and at a high angle to bedding to install an air-vent tower (this is the highest elevation in this area for the pipeline). The tower is about 35 feet (11 m) in elevation above the pipeline. After excavation the area around the tower was backfilled and a concrete facing was placed on the road cut. During strong shaking, cracks developed nearly parallel to the excavation (right angles to the cut) from the surface down to about 20 feet (6 m). Cracks were visible on the hilltop parallel to the vent-cut for a few yards to the northeast.

Ground Rupture

There was ground rupture about 600 feet (180 m) north of the Los Angeles City Aqueduct underpass of the Golden State Freeway. Rupturing took place on an elongate south-trending ridge at an elevation of about 1425 feet (430 m) in a location under the westernmost pipeline. This area is underlain by soil-covered siltstone of the Sunshine Ranch Member of the Saugus Formation. North-trending ground cracks and depressions were observed in a zone about 15 feet (5 m) wide and 40 feet (12 m) long. At the south, a west-trending rupture zone appeared to truncate the cracks and passed under the pipeline, rupturing the foundation and buckling a drain pipe in the process (photo 8). Soil was heaved up near the intersection. This feature plus the buckled drain implied compression and possible faulting. No bedrock was observed; there was a grass cover on the soil, so no definitive information was obtained about the rupture. As a result of ground deformation, the foundations for the pipeline were tilted down on the east and rotated to the south several inches for a distance of about 150 feet (50 m).

Photo 8. Part of the older Los Angeles Aqueduct pipeline just north of the Golden State Freeway where it rotated and slumped. A ground rupture in the Sunshine Ranch Member of the Saugus Formation posses beneath the broken foundation. View is south-southwest.

Cracking in Roads, Road Fills, and Other Fills

Cracks developed in nearly all road fills of any size, as well as in fills adjacent to the aqueduct, freeway underpass, and bridge structures. Extensive cracks were found in both asphalt and concrete road paving.

GROUND SHAKING ON GRADED ALLUVIUM

Buildings of various sorts erected on graded alluvial cover over the Saugus and Mint Canyon Formations were badly damaged by ground shaking.

In downtown Newhall, all of the four existing unreinforced masonry buildings sustained such severe structural damage that they were immediately condemned and demolished soon after*. Other downtown buildings had such minor damage as cracked plaster and broken windows; there was extensive breakage of merchandise shaken from shelves in stores.

Two old wooden frame houses (24739 Walnut Avenue and 24746 Newhall Avenue) were shaken off their foundation supports (two-by-fours placed on end on mudsills) and partially collapsed. Soon after the earthquake, they were condemned and demolished.

Several Southern California Gas Company gas mains in Newhall cracked or were broken. One main caught on fire and burned until mid-morning of February 9 before being extinguished. Another main exploded during the first strong motion, creating an 8-foot-deep (2.5 m) crater. A motorist was driving by at just that moment; his car slid slowly into the crater as the walls began to slip back into the center

* Buildings were Newhall pharmacy, Acorn office supply, Yamaha dealer, and Newhall shoe store.

Photo 9. An 8-foot-deep crater created when a gas main blew up on Pine Avenue just south of San Fernando Road, Newhall. Main blew during first strong motion from the earthquake but fortunately did not catch fire. The car slipped into the crater as the walls began to slide back into the center. *Photo courtesy of the NEWHALL SIGNAL.*

after the initial explosion (photo 9). Fortunately the main did not catch fire; and the motorist escaped unhurt.

Water from a broken main flooded the basement of the Pacific Telephone Company office, damaging equipment and stopping all telephone service to the greater Newhall area. Six pump trucks were required to remove the water, but some service was restored by afternoon. This incident gave rise to the rumor that Newhall was flattened by the earthquake.

In Valencia, buildings in the Old Orchard and Lyons Plaza Shopping Centers sustained such light damage as fallen ceiling panels, wall cracks, and numerous broken display windows. Liquor stores, markets, and drug stores, however, had heavy damage to bottled and canned goods which were toppled over and destroyed. New homes north of Lyons Avenue and west of the Old Orchard Shopping Center had light damage. The toppling of brick chimneys and block walls was common, as was cracking of walls adjacent to window frames. Street and driveway cracks were numerous also.

Thatcher Glass Company in Saugus sustained the most damage to any industry in this entire area. Two of their three furnaces were broken and molten glass oozed from splits down to the floor and around the furnace foundations, melting part of them. The foundation of the third furnace was damaged but not severely. A million or more bottles were broken. About 500 of the 700 employees of the plant were out of work for about two months. Total damage was at least a million dollars.

Directly across San Fernando Road from Thatcher Glass Company, a garage and a pet shop, both made of unreinforced masonry, had extensive structural damage and were condemned and demolished.

Solemint was the hardest hit of any community in the area under discussion. It is only about 5 miles (8 km) northwest of the epicentral area. Not only are most structures on graded alluvium, but water well data indicate there is a relatively high groundwater surface in at least part of the area.

Water level in a Los Angeles County Flood Control well near the intersection of Camp Plenty and Soledad Canyon roads was 30 feet (9 m) below the surface in January 1971; 31 feet on February 10, 1971; and 30 feet in September 1971. During April 1969, the water level was only 7 feet (2 m) below the surface. Another well, about 2000 feet (600 m) east of Solemint Junction and just north of Soledad Canyon Road, showed the following levels below the surface: 9 feet (2.7 m), January 1971; 10 feet (3 m), February 10, 1971; 17 feet (5 m), September 1971.

A prominent north-northeast-trending swarm of discontinuous ground cracks was developed about 4000 feet (1.2 km) west of Solemint Junction. These were well exposed over a zone as wide as 75 feet (20 m) on Soledad Canyon Road, where they broke asphalt paving and curbs and disrupted water lines. Some cracks continued north across the road through a broken block wall and into Plumwood Avenue. Tract homes in this area sustained broken chimneys, block-wall failure, and other street cracking not on line with the prominent swarm. South of Soledad Canyon Road, the swarm of discontinuous cracks could be traced through an open field as far south as the Santa Clara River flood-control levee, a distance of roughly 1000 feet (300 m). The reason for the development of the cracks and their apparent linearity is not known. They may represent a fault zone on which there was little, if any, displacement; they may be a result of localized strong earth motion in alluvium with a high ground water surface; or they may indicate a shelf area in bedrock, now covered by alluvium.

Damage in the North Oaks Shopping Center in Solemint was extensive. The roofs of Grant's Department Store and the Builders Emporium, both made of unreinforced brick, partially collapsed; and, because some of the beams supporting the roof had been shaken away from the brick walls, those sections adjacent to the wall collapsed. Both buildings were completely repaired within two months after the earthquake. All stores in the Shopping Center had extensive damage to goods, and nearly all display windows were broken. Asphalt pavement in the parking lots was cracked.

Tract homes in the Solemint area sustained block-wall failure, chimney damage, and wall cracks. Streets and driveways cracked because of shifting of the road base by shaking.

Mobile-home parks, of which there are several in the Solemint area, had extensive damage. Nearly all the trailers were shaken off their jacks, some so quickly that the jacks pierced the trailer floors. Other trailers were warped during the shaking process. One trailer at the Cordova Mobile Home Park snapped the gas main as it went off the jacks and burned. All of the 280 mobile homes in the Park sustained at least $500 damage.

Damage in Friendly Valley, south of Solemint Junction, was significant but not severe. Windows in commercial buildings were broken, and there was some wall and merchandise damage. Tract homes in this area showed block-wall, chimney, and other minor damage. Streets cracked. All water service to Friendly Valley was stopped on February 9, as main lines broke in two places.

GROUND SHAKING IN THE CRYSTALLINE ROCKS

Most damage in this geologic environment was restricted to roads, road cuts, and fills. Rock falls and debris flows were common on steep slopes in the northern part of the San Gabriel Mountains, but because the area is little developed there was little damage to structures. The largest known rockfall took place on the steep and fractured slopes of the Schmitt Quarry in the central part of Section 16 about a mile and a half east of Lang, adjacent to Soledad Canyon Road.

There were small slides in road cuts, extensive cracks in asphalt paving, and cracks in every road fill along Sand Canyon and Little Tujunga roads from Live Oak Campground to at least the Pacoima Reservoir area. Cracks in nearly every fill paralleled the road, and cracks in the asphalt paving were commonly at high angles to the road center line. This section of road was closed for several days after the earthquake.

Placerita Canyon Road was similarly damaged from the west edge of the State Park to within about a mile of its intersection with Sand Canyon Road. Within a day, debris was cleared away so that traffic could pass. There was similar damage to Soledad Canyon Road. Road cracks and minor slides occurred locally from just west of Soledad Guard Station all the way to Ravenna.

An unusual condition developed on a road-cut failure about a mile east of the Soledad Campground on Soledad Canyon Road. The steep, irregular cut is on fractured anorthosite cut by numerous irregularly shaped dark, fine-grained dikes. Adjacent to the cut and about 50 feet (15 m) above road level is a home on a cut-and-fill pad. A well-reinforced block wall was built near the edge of the cut. During strong shaking, parallel cracks developed on both sides of the wall. Near the center of the wall, rock broke out from under, leaving an air gap and several yards of the wall foundation exposed. Because of the steel reinforcement in the block wall, it did not fail. From road level, the wall now looks, in part, like a bridge (photo 10).

GROUND CRACKING AND SHAKING IN THE SAUGUS FORMATION

Most damage in this geologic environment was restricted to roads, road cuts, and fills. Rock falls and debris flows were common on steep slopes in the northern part of the San Gabriel Mountains, but because the area is little developed there was little damage to structures. The largest known rockfall took place on the steep and fractured slopes of the Schmitt Quarry in the central part of Section 16 about a mile and a half east of Lang, adjacent to Soledad Canyon Road.

In the Rye Canyon Facility of Lockheed Aircraft Company northeast of Castaic Junction, walls in several buildings were cracked from ceiling to floor. Asphalt paving on the parking lot for the main office building had numerous cracks, but the cracks did not extend into the surrounding ground.

There were ground cracks developed in one area of the Princess Estates. The highest hill in the tract had been graded on nearly flat-lying beds of the Saugus Formation. Here, at the end of Goldstream Way, a generally west-trending crack swarm was developed. The swarm was about 100 feet (30 m) wide, roughly 200 feet (60 m) long, and ended at a cliff face on the east. Observations on the cliff face indicate that the cracks were nearly vertical and did not extend down more than 20 to 30 feet (6 to 9 m). The concrete slabs for two unfinished houses and the asphalt paving on Goldstream Way were cracked also.

Photo 10. Scars left by debris fall from steep cut on fractured anorthosite. Area is on Soledad Canyon Road about 1 mile east of Soledad Campground. Block wall was completely reinforced with steel and did not fail even though undermined.

CHAPTER 10

Seismically Triggered Landslides in the Area Above the San Fernando Valley

by Douglas M. Morton [1]

Thousands of landslides were triggered by the San Fernando earthquake of February 9, 1971, in an area of 250 km^2 in the hilly and mountainous terrain above San Fernando Valley. A few pre-existing slides were activated, and many new slides formed. The gross distribution of the slides was controlled primarily by the intensity of ground shaking, but important local variations in the density of landslides reflect variations in the character and structural history of local geologic formations (table 1). Some landslides were localized along fault breaks. The earthquake also produced some areas of highly fractured rock, especially along ridge tops, that are likely to give rise to abundant landslides or mudflows when saturated.

This report updates earlier reports (Morton, 1971a, 1971b) summarizing a photointerpretive investigation of landslides triggered by the earthquake. The investigation used black-and-white aerial photographs taken for the U.S. Geological Survey on February 10, 1971, (American Aerial Surveys, Inc., scale 1:10,000); color photographs taken on February 18, 1971, (U.S. Air Force, scale 1:20,000); black-and-white photographs taken on February 12, 1971, (American Aerial Survey, scale 1:2400); and black-and-white photographs taken between June 1 and 21, 1971, (I. K. Curtis Services, scale 1:2400 and 1:6000). The landslides are plotted on plate 3 (this Bulletin).

Additional landslides in parts of the area were plotted by A. G. Barrows, J. E. Kahle, and F. H. Weber, Jr; C. Delao, Los Angeles County Flood Control District, provided rainfall data for the December 1971 storms.

Table 1. Lithology of Quaternary and Tertiary formations

Formation	*Description*
Quaternary alluvial and terrace deposits	Stream-channel and flood-plain deposits consisting of a great variety of unconsolidated and loosely consolidated brownish and grayish "dirty", unsorted, angular to subangular detritus of local origin; some local cementation.
Pleistocene Pacoima	Poorly sorted fanglomerate or sedimentary breccia consisting of sharply angular pebbles and boulders of wide size range deposited with a dark brown or reddish-brown mudstone-soil matrix. Crudely bedded or unstratified; lightly cemented in some places.
Pleistocene Saugus	Light-colored, poorly sorted, loosely consolidated conglomerate and coarse sandstone, commonly crossbedded; deposited as fluviatile and alluvial-fan sediments around the western end of the San Gabriel Mountains. Much of it is quite well cemented and will stand in very steep slopes without failure. Red and greenish mudstone and sandstone in lower part.
Pliocene Towsley-Repetto	The base of the "Towsley" may be late Miocene; "Repetto" is early Pliocene; and "Pico" is usually middle and late Pliocene. These are well-stratified marine sedimentary rocks which are predominantly sandstone but range from siltstone to conglomerate. Massive lenticular conglomerate beds occur in some sections of all three units. There is a great deal of siltstone and fine sandy shale in the Repetto unit which tends to break down or disintegrate when water-saturated. The thickbedded conglomerate members tend to maintain steep and resistant slopes.
Modelo	Wide lithologic variation and lenticularity of strata characterize the Modelo, but fine to coarse arkosic sandstone and conglomerate make up the largest proportion. Thin-bedded siliceous, calcareous, silty, and diatomaceous shales are, nevertheless, the most distinctive and typical lithologies of this formation.

[1] Geologist, California Division of Mines and Geology, at the time of the earthquake. Now with the U.S. Geological Survey.

LANDSLIDING

Although landsliding was a direct and immediate response to ground rupture and shaking during the earthquake, some rockfalls continued for several days along steep canyon walls (for example, Pacoima and Little Tujunga Canyons). Some of these rockfalls may have been triggered by aftershocks. The landslides were concentrated south-southwest of the epicenter of the main shock, along and adjacent to the area of tectonic surface rupture, and within the area of principal aftershocks.

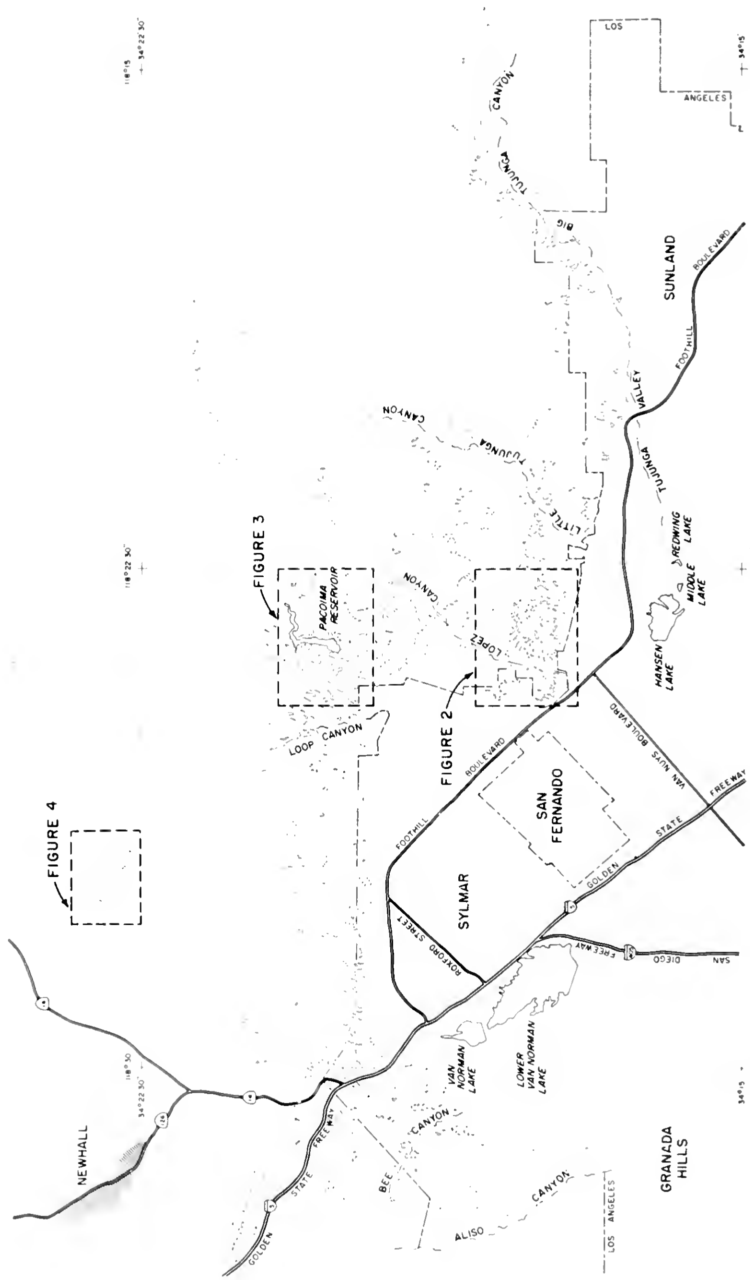


Figure 1. Distribution of larger seismically triggered landslides, San Fernando Valley area.

Local variation in landslide density reflected the character of local rock units (table 1), degree of fracturing and faulting, and the presence of already formed landslide deposits. Physiography apparently controlled the density of landslides only where slopes were extremely steep.

Of the thousands of landslides generated or reactivated, only the larger ones and those whose displacement was sufficient to produce landslide morphology or to give rise to bare areas stripped of vegetation could be mapped from the aerial photographs (figure 1). Landslides within the valley area were not studied; for the nature of those landslides see Youd, 1971, and Smith and Fallgren, this Bulletin.

TYPES OF SLOPE FAILURES

Rockfalls, soil falls, debris slides, avalanches, and slumps were the principal types of landslides triggered by the earthquake. Surficial (0.2 to 1 m thick) debris slides and avalanches were probably the most widespread and common types of failure and were especially pronounced in areas underlain by sedimentary rocks (photo 1). Some minor failures were localized along a single bed in a sedimentary sequence (photo 2). Rockfalls were common on steep-walled canyon faces cut in well-fractured basement rock but also occurred in sedimentary rock where a particularly resistant bed cropped out on oversteepened slopes (photo 3). Soil falls occurred mainly at the free face of recent stream terrace deposits along major drainages but were also common along some ridges. Slumping took place largely on reactivated, pre-existing (pre-earthquake) slumps (photo 4).

Some landslides in the hilly area, especially between Big and Little Tujunga Canyons (Lakeview fault segment), resulted from primary fault displacement (Kahle, this Bulletin). This landsliding originated by a combination of shaking and concomitant oversteepening due to thrusting of upper plate material upward and southward towards the valley. These landslides are only along the lines of fault rupture (photo 5).

The relationship of landsliding to the intensity of

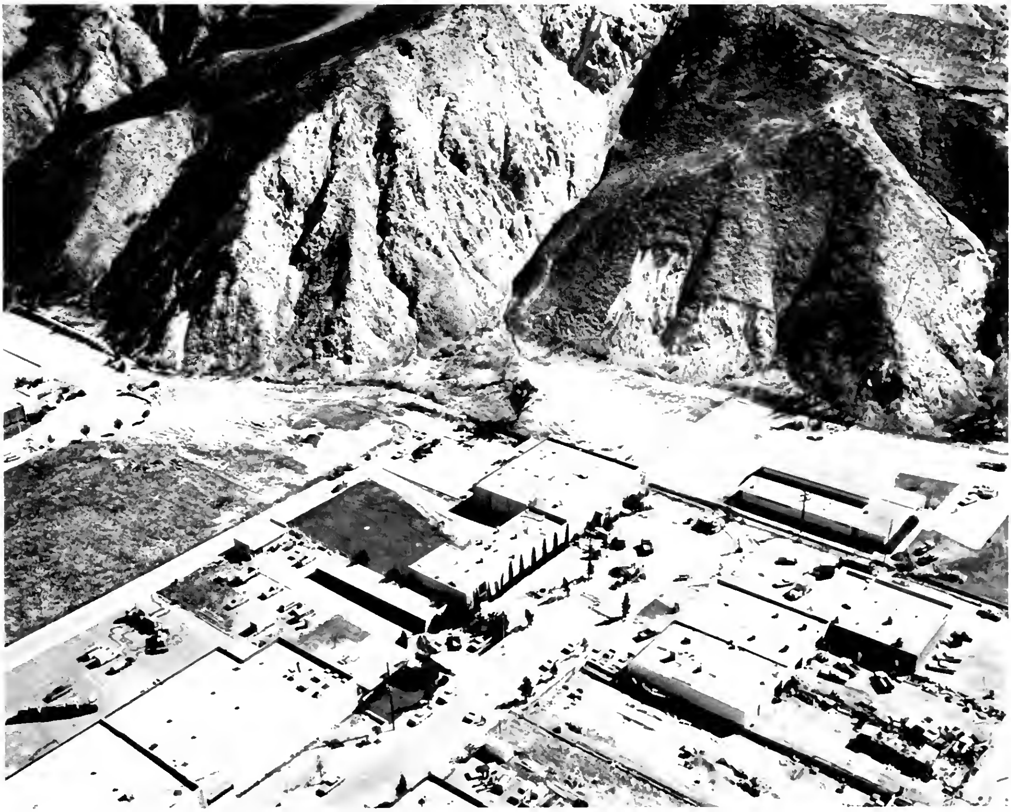


Photo 1. Abundant shallow small slope failures in Towsley and Modelo Formations near San Fernando Ranger Station. *Photo courtesy of Los Angeles Department of Building and Safety.*

Photo 2. Landslides localized along individual beds within the Towsley-Pico Formations (undifferentiated) and the Modelo Formation east of Lopez Canyon.

Photo 3. Landslide in oversteepened Pico Formation, south end of San Fernando Pass. *Photo by James E. Kahle.*

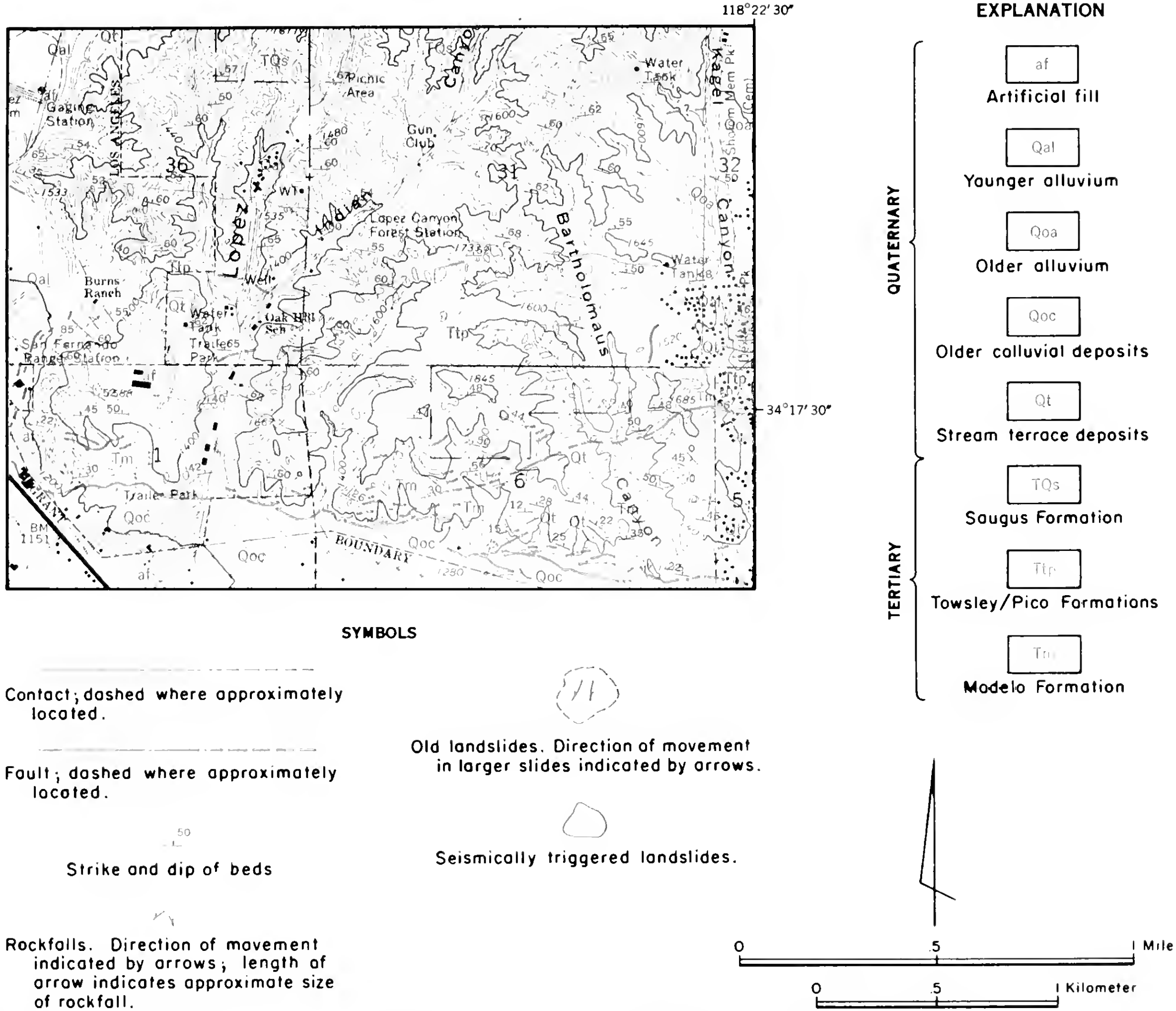


Figure 2. Geologic map showing lithologic control on landslide distribution, Lopez Canyon area. (Geology after Allan G. Barrows, plate 2, this Bulletin).

Photo 4. Renewed movement in pre-earthquake landslide in Modelo Formation east side of Schwartz Canyon. *Photo courtesy of Los Angeles Department of Building and Safety.*

shaking is particularly clear in the westward-striking Pico, Modelo, Towsley, and Saugus Formations west of the San Fernando Valley. There, the number of landslides decreases markedly along strike westward from the valley, away from the area of aftershocks and most intense tectonic rupturing.

Previously weakened rock commonly failed. A number of old landslides were reactivated, as shown by fresh scarps from 0.25 to about 10 m high (photo 4). Some small oversteepened old scarps failed as debris slides. Other large, old slides failed in part, generating a number of small new slides generally concentrated along the toe of the old slide (for example, in Pacoima Canyon, figure 3). Other landslides were localized by crushed rock along older, inactive fault zones. Thus, the San Gabriel fault zone was the locus of a narrow band of landslides north of Placerita Canyon (figure 4).

Landslides were also common in excavations, and many roads were blocked by failures in cut slopes (photo 6). There were innumerable minor rockfalls in roadcuts in the area of figure 1 and eastward throughout most of the San Gabriel Mountains. Fill failure was common.

Large rotational or complex landslides, which are characteristic of the San Gabriel and Santa Susana Mountains (Morton and Streitz, 1969; Saul, this Bulletin), did not form during the San Fernando earthquake. Apparently such slides form under different circumstances; for instance, without seismic shaking at times when the ground is saturated by prolonged or heavy rain or by seismic shaking with longer period vibrations or of longer duration than the San Fernando earthquake.

Ground fracturing throughout most of the area of figure 1 is closely related to landsliding. Fracturing, not accompanied by landsliding, appears to be most pronounced along ridge tops, where, given sufficient rainfall, the highly fractured surficial materials may give rise to abundant debris slides and flows. These materials may now conceivably have the potential for generating more landslides than were triggered during

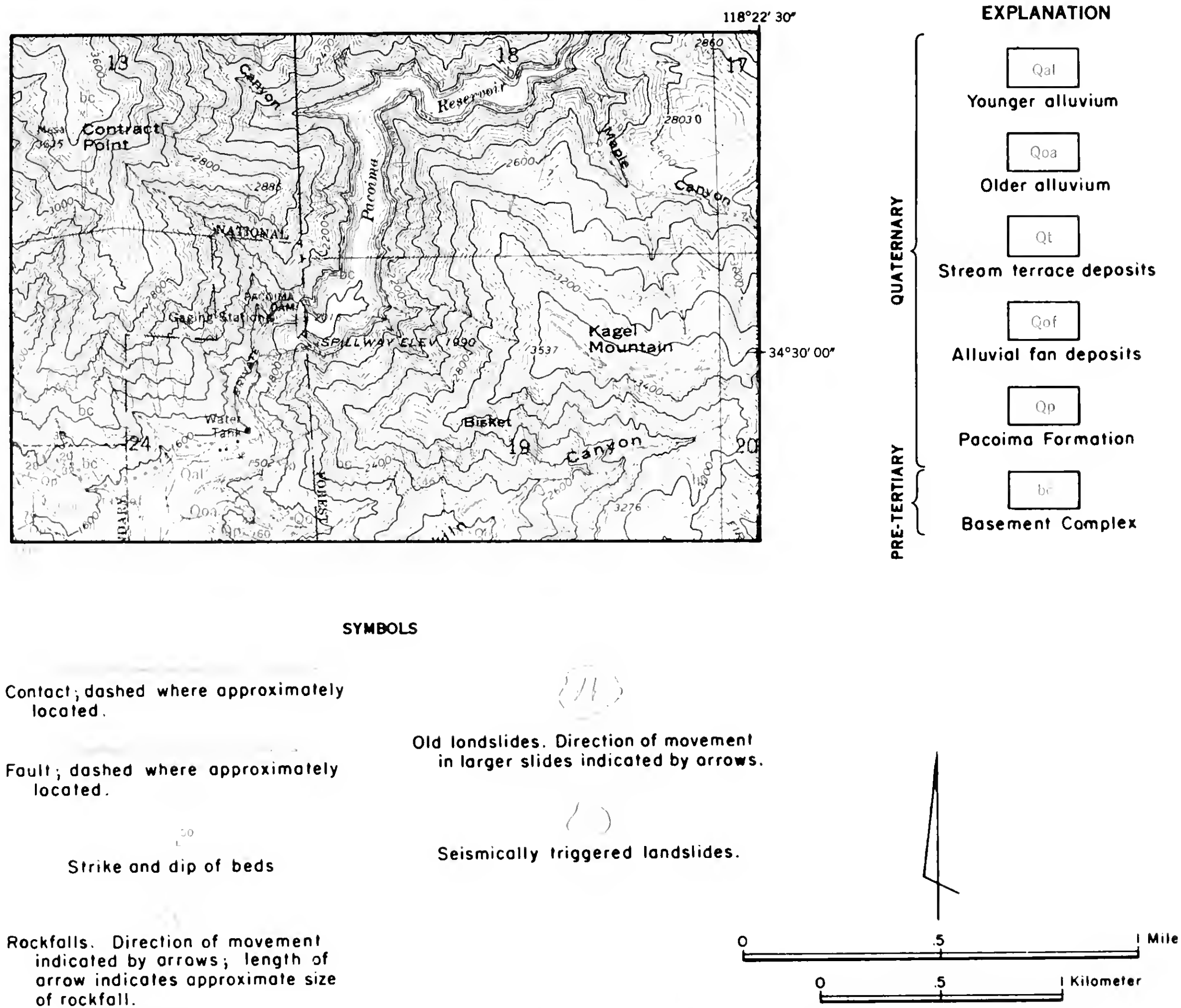


Figure 3. Geologic map showing topographic control of landslide distribution along the steep walls of lower Pacoima Canyon and multiple small slides in pre-earthquake landslide deposit (northeast corner). (Geology after Allan G. Barrows, plate 2, this Bulletin).

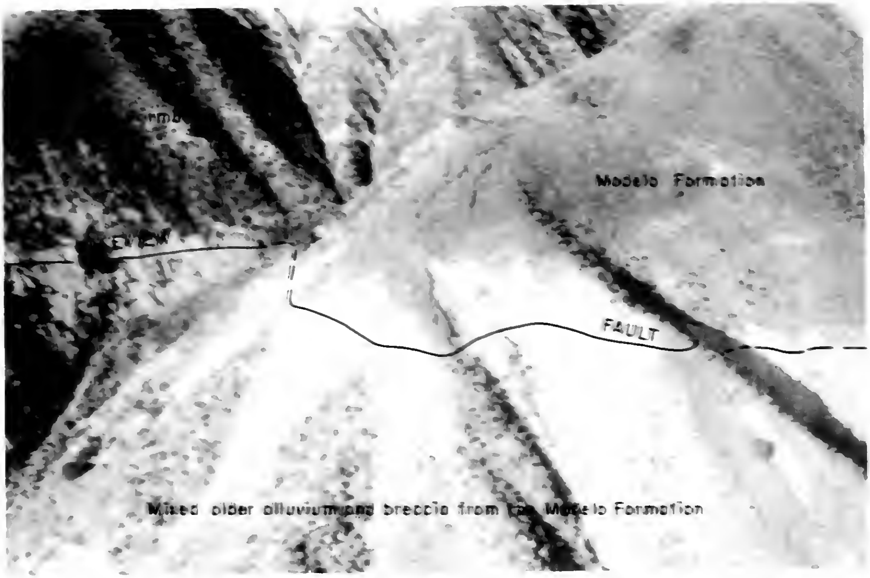


Photo 5. Landslides localized along the Lakeview fault just east of Schwartz Canyon. (Geology after J. E. Kahle, plate 2, this Bulletin.)

Photo 6. Landslide in cut-slope adjacent to U.S. Highway 99 (Golden State Freeway), north side of San Fernando Valley. Photo by James E. Kahle.

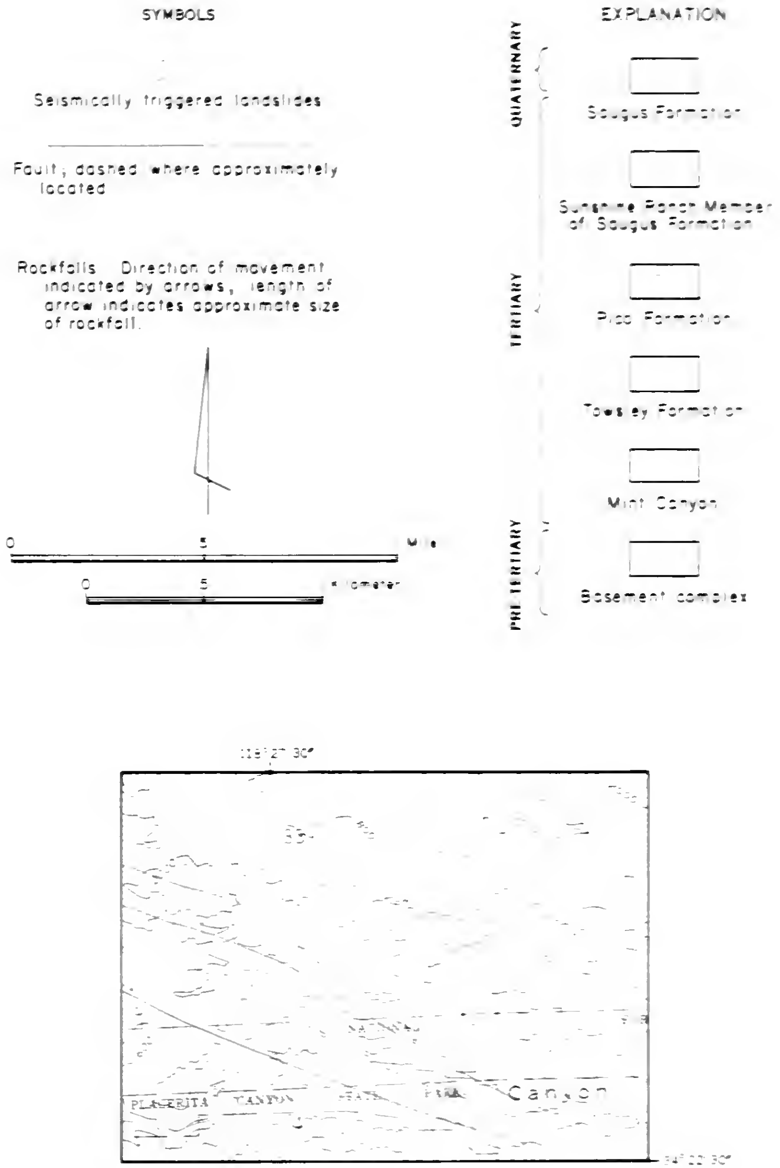


Figure 4. Generalized geologic map showing localization of landslides along weak earth materials in the San Gabriel fault zone, Placerita Canyon area. (Geology from Richard B. Saul, work in progress, Mint Canyon quadrangle.)

the earthquake. However, rains during December 1971 totaling 5 to 7 inches in the area resulted in no significant failures in this fractured rock. This indicates that greater rainfall is required to initiate failures. Lawson (1908, p. 386) noted that cracks developed without landslide movement during the 1906 San Francisco earthquake. Heavy rainfall during the following 1906–07 winter produced many slides in this fractured ground, which Lawson attributed directly to the combination of fractured ground and rainfall.

DISTRIBUTION OF LANDSLIDES

Landslide distribution controlled by rock type is best seen in the vicinity of Lopez and Bartholomaus Canyons (figure 2 and table 1). Here, numerous landslides formed on outcrops of the Modelo and Towsley Formations, while relatively few formed on the immediately adjacent Saugus Formation. There were numerous rockfalls where highly fractured basement rock was exposed on steep slopes, especially along such major drainages as Pacoima, Little Tujunga, and Big Tujunga Canyons. Rockfalls at the mouth of Pacoima Canyon (figure 3) covered sizable areas but apparently consisted only of surficial material.

In general, landsliding occurred where there has been little residential development, largely because of the steepness of the natural slopes. Had some areas been extensively developed, such as the hilly portion west of Little Tujunga Canyon, landsliding would probably have exacted a considerable toll. In addition to the failure of natural materials, failures in fill would be likely, as evidenced by widespread failures of such material elsewhere during the earthquake.

CHAPTER 11

Trenches Dug Across Surface Breaks of the San Fernando Fault

by the California Division of Mines and Geology
in cooperation with F. Beach Leighton & Associates

Brief descriptions of the findings in fifteen backhoe trenches dug by the California Division of Mines and Geology in cooperation with F. Beach Leighton and Associates are given here. Trenching was done in April 1971 to examine the active San Fernando fault zone in detail. Logs of the trenches were made by E. G. Heath and R. H. Dickey of F. Beach Leighton and Associates and by J. E. Kahle and A. G. Barrows of the Division of Mines and Geology. Logs of the trenches may be consulted in the Los Angeles District Office of the Division of Mines and Geology. Trench locations are shown on plate 3. The log of trench 8 is shown on plate 4.

Trench 1: Lopez Canyon. Trench across the Oak Hill fault scarp. Bedding-plane fault strikes N. 75° W., dips 62° N., and is nearly coincident with attitude of sandstone, siltstone, and conglomerate strata. Displaced base of slope wash and alluvium is 81 cm (32 inches) down on the south side.

Trench 2: Lopez Canyon. Trench across mole track of Oak Hill fault in unconsolidated fill and alluvium. Although surface is cracked, no faulting was observed in the trench.

Trench 3: Ridge north of Carl Street. Trench across compression ridge exposed well-defined single fault plane that strikes east-west, dips 44° N., and coincides with attitude of overlying bedding. Fault juxtaposes Modelo shale on the north over colluvial debris with coarse sandy matrix which may be an alluvial fan or debris flow deposit.

Trench 4: Ridge west of Blue Star Trailer Court and north of Paxton Street. Trench across 60 cm (2-foot) scarp in soil exposed near-surface aspect of fault plane that separates Modelo debris on the north containing shale chips, pebbles, and cobbles from poorly bedded old alluvium and colluvium, on the south. In most of the exposure, the fault plane dips north 15° but bends over near the surface and dips shallowly southward.

Trench 5: Pacoima Wash near Newton Street. Trench across 30 cm (1-foot) scarp of Sylmar fault segment. Fault could not be seen in the unconsolidated, bouldery alluvium. Caving limited exposure to 1.2 m (4-foot) depth.

Trench 6: Big Tujunga Wash, south of Big Tujunga Creek. Trench across 50 to 60 cm (20- to 24-inch) scarp in modern, flat-lying, bouldery alluvium. Directly beneath the surface offset, a jumbled zone dips approximately 45° northward; but coarseness of material and lack of marker units made it difficult to determine whether faulting had occurred.

Trench 7: Big Tujunga Wash, north of Big Tujunga Creek. Trench across 38 cm (15-inch) scarp. Flat-lying to shallowly south-dipping, sandy and bouldery, moist alluvial layers, which are overlain by soil and fill, vaguely appear to be folded beneath scarp. May represent a dispersion of a discrete fault plane in unconsolidated materials.

Trench 8: Blue Star Trailer Court, west side of Lopez Canyon. Trench across 70 cm (2.3-foot) scarp in graded bedrock surface. Movement during earthquake took place on two parallel fault planes that coincide with the N. 80° W. strike and 32° N. dip of bedding in Modelo siltstone and sandstone. Near the surface, however, the northernmost fault plane bends over and becomes horizontal. Trench also exposed north-dipping undisturbed fault contact between overlying highly contorted Modelo sandstone strata and reddish-brown alluvial and colluvial debris (see plate 4, this Bulletin).

Trench 9: San Fernando Valley Juvenile Hall grounds. Trench across main trace of northern set of cracks in football field. Main crack was traced in moist sandy and silty soil containing abundant roots to a depth of 1.7 m (5.5 feet) to the upper surface of a gravelly layer where it appeared to stop. This suggests that movement took place along the surface of the gravelly layer. See Smith and Fallgren, this Bulletin, for background on Juvenile Hall area.

Trench 10: San Fernando Valley Juvenile Hall between inner and outer compound. Trench across trace of southern set of cracks. Main crack strikes N. 10° W. and extends nearly vertically 2.75 m (9 feet) to bottom of trench through layers of silty sand, many with high organic content.

Trench 11: South of San Fernando Road opposite San Fernando Valley Juvenile Hall. Trench in open field across sand boil. Light brown, sand-filled crack was traced 2.75 m (9 feet) from center of sand boil to bottom of trench in dark brown silty sand. The filled crack represents the fracture through which material travelled to surface during formation of the sand boil. Its total depth is unknown.

Trench 12: Vacant lot at 12670 Gladstone Avenue, Sylmar. Trench across surface cracks aligned with fault scarps east and west of lot. No significant breaks were seen in the unconsolidated pebbly to bouldery conglomerate and interlayered sand strata although strata appeared to bend to conform to surface warp or scarp.

Trench 13: North shoulder of Foothill Freeway, west of Maclay Street. Trench across 30 cm (1-foot) E–W scarp or warp. Fault plane dipping 52° N. was traced as a zone of looser material separating gravelly and cobbly deposits with a reddish sandy matrix on the north from adobe-like material of possible mudflow origin on the south.

Trench 14: West side of Tyler Street, 60 m (200 feet) northeast of Herrick Avenue, Sylmar. Trench across NW-striking crack. Not possible to trace crack in loose trash and fill exposed in walls of trench.

Trench 15: West of road to St. Vincent de Paul Camp, east of Bee Canyon. Trench across minor cracks possibly coinciding with the trace of the Santa Susana fault. Not possible to follow cracks in loose, powdery soil exposed in walls of trench. No graphic log available.

CHAPTER 12

Ground Displacement at San Fernando Valley Juvenile Hall and the Sylmar Converter Station[1]

by Jay L. Smith [2] and Richard B. Fallgren [2]

The San Fernando Valley Juvenile Hall and the Sylmar Converter Station were severely damaged during the earthquake of February 9, 1971. Although located in a region of moderate to heavy shaking (Modified Mercalli intensity about VIII), the damage to these facilities was unusually severe owing to ground displacement. Results of investigations conducted for the County of Los Angeles and the Department of Water and Power of the City of Los Angeles have shown that local soil and geologic conditions were responsible for ground displacement and damage (Fallgren and Smith, 1971a and 1971b).

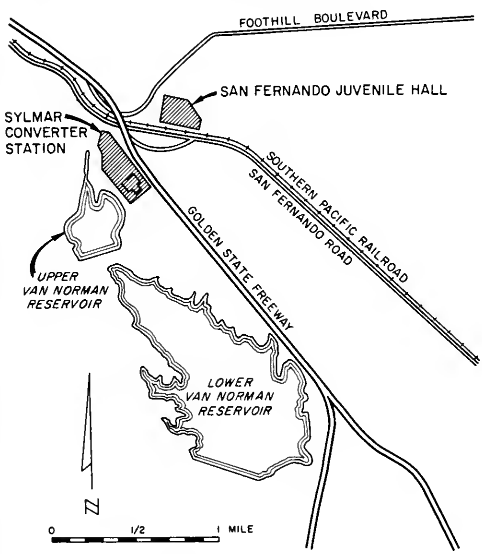


Figure 1. Vicinity map.

Both the Juvenile Hall, a juvenile-detention facility, and the Converter Station, a major terminus of electric power transmission from the Pacific Northwest, are near the Upper Van Norman Reservoir (figure 1). The area is approximately 7½ miles south of the epicenter of the February 9 earthquake and 2½ miles northwest of the known surface ruptures along the Sylmar segment of the San Fernando fault. Damage to the facilities resulted from severe shaking and differential ground movement. Heaviest damage to buildings was in the vicinity of the permanent ground displacement (Youd, 1971).

ZONE OF DISPLACEMENT

The limits of the zone of displacement are indicated by the pattern of ground-surface ruptures shown on figure 2. The zone is 4000 feet long with a maximum width of 900 feet. It extends from a point 500 feet northeast of the Juvenile Hall to within the Sylmar Converter Station site at the edge of Upper Van Norman Reservoir. The ground surface descends approximately 40 feet in elevation along the length of the zone, an average slope of about 1 percent. Movement within the zone was downslope in a southwest direction. The north boundary of the zone bisects the Juvenile Hall site and transects the southeastern third of the Converter Station site. Ground ruptures along this boundary indicate right-lateral slip, and the trend of major cracks is generally parallel to the direction of movement of the displaced zone. The south boundary of the zone crosses the southeast corner of the Juvenile Hall site and extends into the Converter Station site south of the main building. Ground ruptures along this boundary are characterized by left-lateral slip, and the larger cracks generally trend nearly north in an *en echelon* pattern, approximately 45 degrees to the direction of gross movement.

The amount of relative lateral movement within the displaced zone (figure 3) is based on measured offsets of curbs and property lines crossing the zone. These offsets indicate as much as 5 feet of relative lateral movement at the Juvenile Hall site. The same magnitude of relative movement occurred as far to the southwest as Sepulveda Boulevard, adjacent to the Converter Station. However, southwest of the drainage channel, which separates the Converter Station from Sepulveda Boulevard, the lateral movements measured were no greater than 2 feet.

The ground cracks were examined to depths of 15 feet in trenches excavated across the displacement-zone boundaries at the Juvenile Hall and southwest of San

[1] Submitted for publication June 30, 1972
[2] Fugro, Inc., Long Beach, California

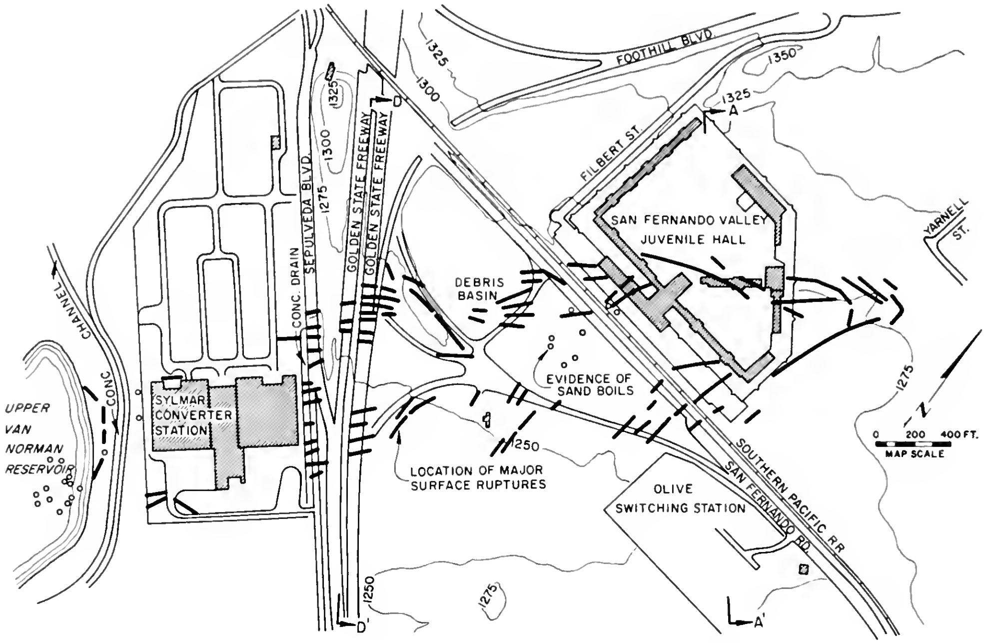


Figure 2. Location of ground surface ruptures in the zone of displacement.

Fernando Road. In general, the cracks died out and curved inward with depth toward the interior of the zone of displacement. Figure 4 represents the conditions encountered in a trench trending nearly north across the north boundary of the zone on the Juvenile Hall site. The largest crack coincides with a 7-inch vertical displacement of the ground surface, and underlying soil contacts are similarly displaced. Near the bottom of the trench, however, the crack is coincident with a displaced soil-contact that has almost twice the amount of offset of higher strata. In view of the lateral continuity of the boundaries of the involved soil horizons, such a difference must represent evidence of prior displacement. Narrow vertical zones of soft soil, truncated at the top by alluvium and fill soil, were also found. Since vertical displacement is not apparent, these zones most probably represent loosely filled tension cracks produced by displacement prior to 1971.

GEOLOGIC AND SOIL CONDITIONS

Juvenile Hall and the Sylmar Converter Station are near the intersection of Grapevine Canyon and Weldon Canyon, both south-draining valleys of the San Gabriel Mountains (figure 5). These valleys, and others immediately to the east and west, have steep flanking ridges and gently sloping alluvial fans at their mouths. The fans have accumulated in a northeast-trending depression in the Saugus Formation between the San Gabriel Mountains and the Mission Hills. This depression generally coincides with the projected trend of the Mission Hills syncline (Merifield, 1958).

The east-flanking ridge of Grapevine Canyon extends into the northwest corner of the Juvenile Hall site. The ridge is underlain by siltstone, sandstone, and conglomerate of the Saugus Formation. The maximum depth to bedrock beneath the Juvenile Hall site and in the central part of the depression is unknown. Bedrock is not exposed at the Converter Station site.

The alluvial fans beneath the Juvenile Hall site developed during late Pleistocene and Holocene time at the mouths of Grapevine Canyon and smaller valleys immediately east. They were deposited chiefly by torrential streamflow and occasional mud-flows. Large composite fans have also developed below Sombrero and Weldon Canyons. As a consequence of the merging of three fans—the Weldon fan from the northwest, the Grapevine fan from the north, and the Sombrero fan from the northeast—a lowland has developed at their intersection in the area between Juvenile Hall and Upper Van Norman Reservoir, including the Converter Station.

The properties of the alluvium in the vicinity of the sites were investigated by means of bucket-auger borings as deep as 80 feet and by penetrometer soundings along the Golden State Freeway. The profile of materials along a section-line crossing the Juvenile Hall from northwest to the southeast is shown in

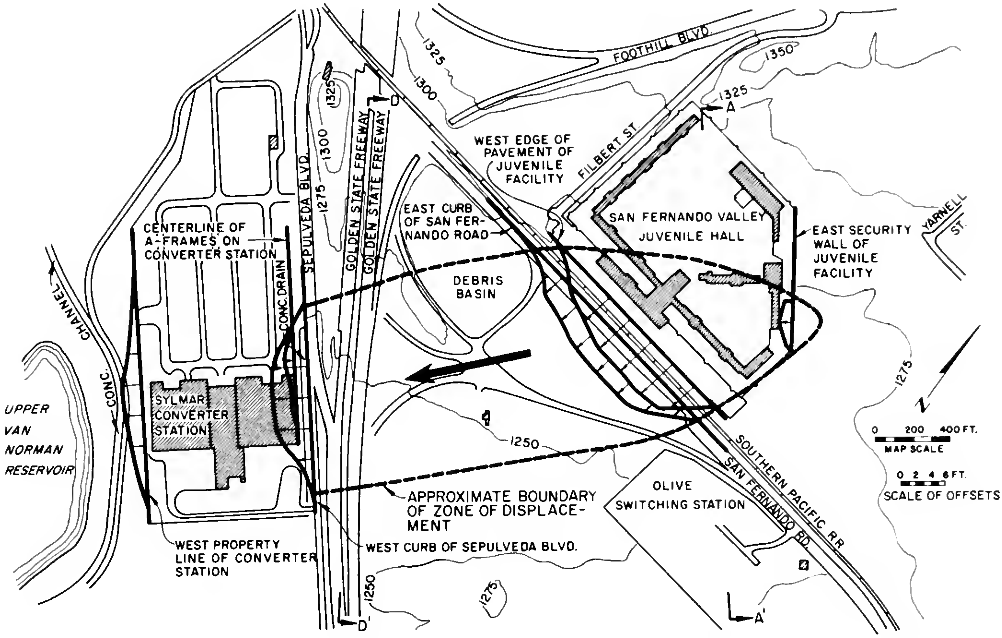


Figure 3. Relative lateral ground movement in the zone of displacement.

figure 6. This section is taken along a line transverse to the direction of movement within the zone of displacement. The sand and silt are typical of material near the termini of most merging alluvial fans. The significant feature, however, is the existence of a soft, saturated zone underlying the dense, dry upper zone. Alluvium in the soft zone consists of sandy silt and fine sand of a uniform texture. A similar profile was disclosed in a penetrometer survey by the California Division of Highways (C. E. Marek, written communication, September 1971) along the Golden State Freeway (figure 7).

Contours of depth to ground water in the vicinity of the Juvenile Hall are based on data from the recent bucket-auger borings and from nearby wells. The ground water surface generally conforms to the topography, being nearest the ground surface in the low area south of the Juvenile Hall. (See, also, paper by Brown, this Bulletin).

The location and size of ground ruptures along the

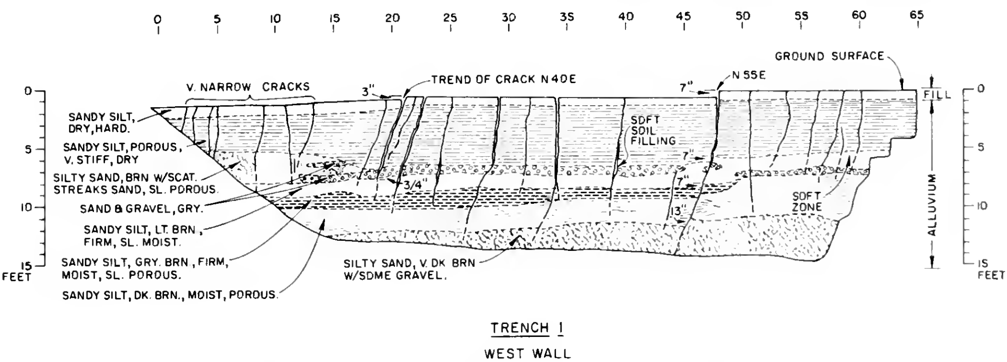


Figure 4. Exploratory trench across ground ruptures on the Juvenile Hall site.

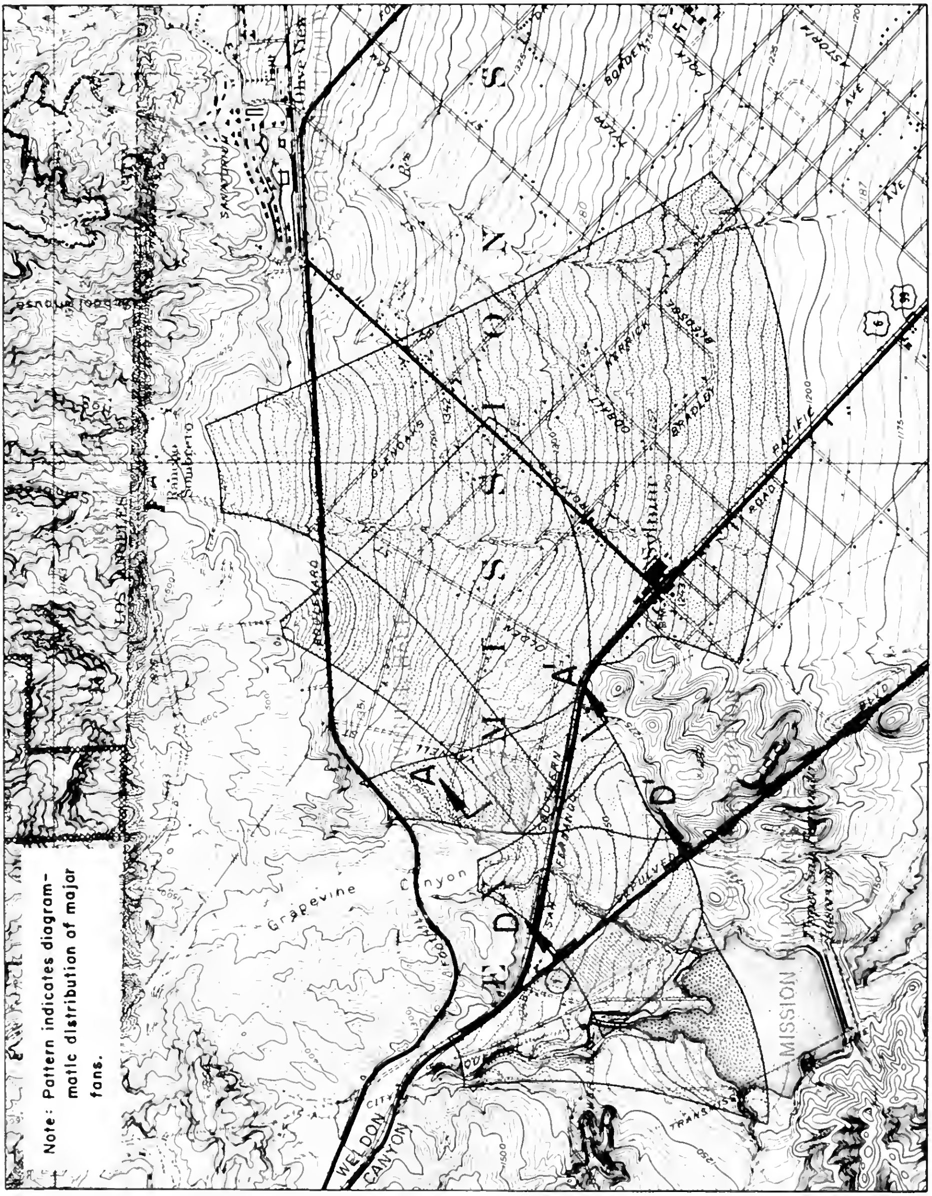


Figure 5. Topography as shown on 1935 Sylmar quadrangle.

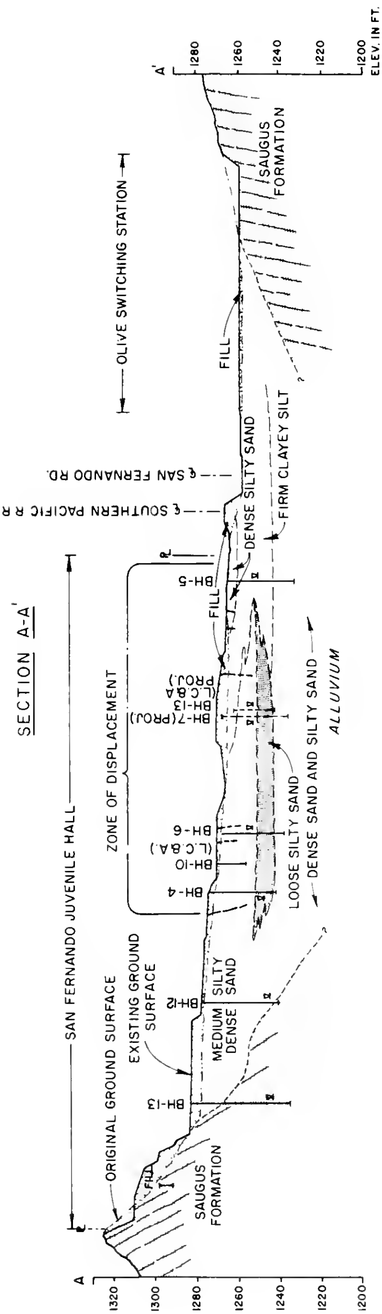


Figure 6. Geologic and soil profile across the Juvenile Hall site.

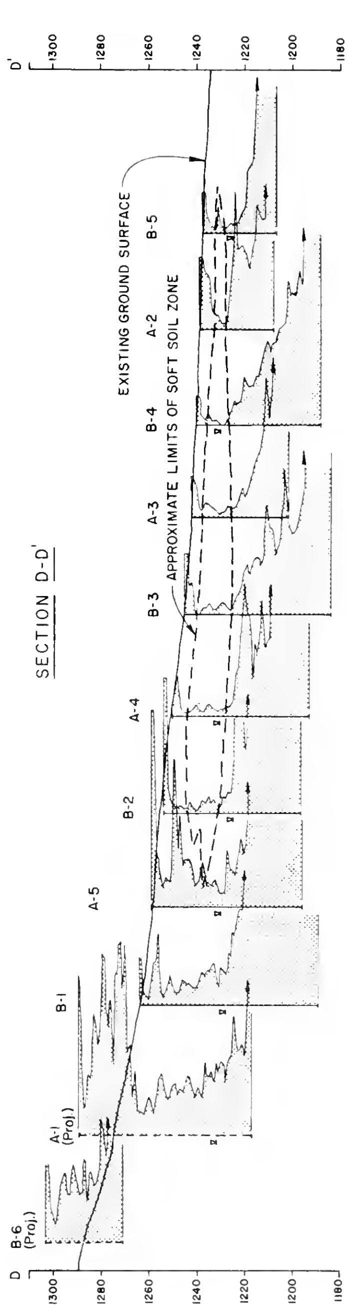


Figure 7. Soil profile along the Golden State Freeway as indicated by penetrometer survey.

boundaries of the zone of displacement are related to the existence of relatively brittle surface soils, both natural and fill. The natural surface soils, where exposed on the Juvenile Hall site, consist of hard, dry, and slightly cemented clayey sand to a depth of several feet. An exposure of this is shown in photo 1, where the underlying softer soils have been consolidated by the blast from a small dynamite charge during a seismic refraction survey. The fill soils, because of their relatively dense and dry conditions, are also brittle as compared to the moist deeper soils. Long and relatively continuous ground ruptures along the north boundary of the displacement zone were generally found in the crust-like soils described above. Due to the lack of brittle surface soils, surface ruptures along the south boundary were shorter and less well developed, tending toward an *en echelon* pattern.

A generalized profile near the center of the displaced zone, based on the borings, shows 20 feet of medium dense and moist silty sand overlying a 10-foot-thick layer of soft, saturated sandy silt and fine sand. The response of this soil to lateral forces generated by the earthquake would result in large, nonelastic shearing strains throughout the depth of the soft soil layer. Shear strain in this layer during the San Fernando earthquake may have resulted in a maximum net downslope lateral displacement of the ground surface on the order of 3 inches during each cycle of strong shaking. The San Fernando earthquake produced about 20 cycles of strong shaking. Therefore, a total ground surface displacement of about 5 feet can be accounted for in this way. Displacement away from the center of the zone of movement was less, depending on the thickness and consistency of the soft layer.

Some of the saturated soils in the zone of displacement consist of uniform, fine sand with a mean grain size between 0.075 and 0.2 mm. These soils have a potential for liquefaction during strong shaking (Seed, 1971). The existence of sand boils in the high ground water area southeast of Juvenile Hall is evidence of this local liquefaction. However, soils with liquefaction potential are not sufficiently widespread throughout the zone of displacement to account for the lack of stability of the area during the earthquake. The soft and loose saturated soils have sufficiently low strength under static conditions to account for the downslope ground movement during strong shaking. Large-scale liquefaction would have resulted in much greater displacements. It is concluded, therefore, that liquefaction played a minor role in the performance of the site during the earthquake.

Two northeast-trending faults have been recognized in the San Gabriel Mountains immediately above Olive View Hospital (figure 5). These are the Olive View and

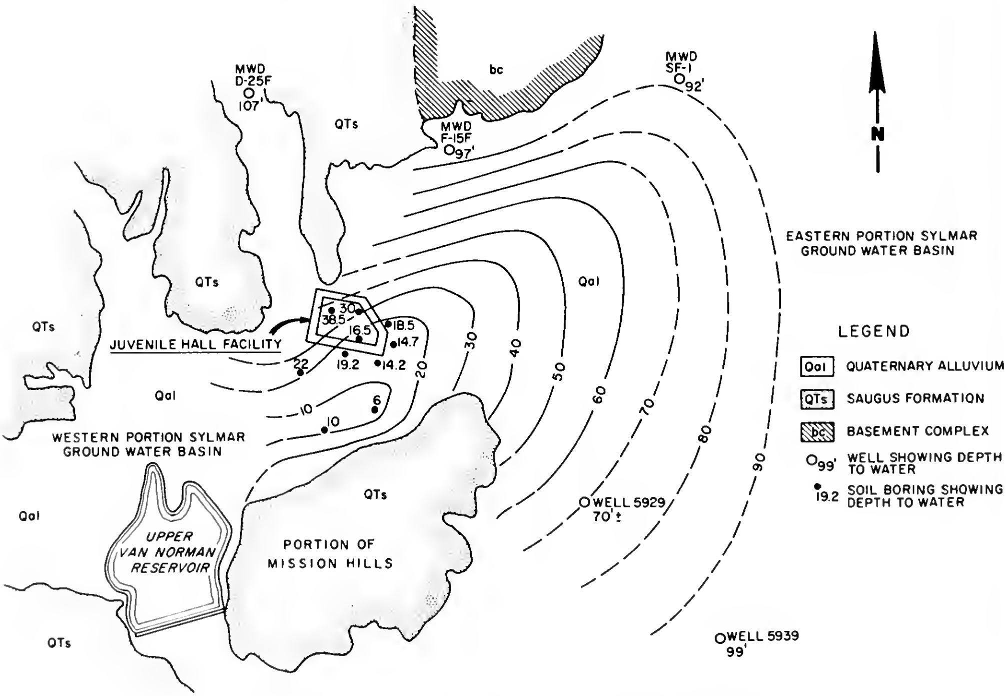


Figure 8. Depth-to-water contours. By Glenn A. Brown and Associates, September 1971

Photo 1. Crater resulting from consolidation of soft soil by a small dynamite blast during seismic refraction survey.

North Olive View faults (Proctor, 1968). Projection of one of these faults to the southwest through the site was made by Merifield (1958). A careful examination was made of the hillside exposure of these faults after the earthquake of February 9. There are irregular and discontinuous cracks associated with slumping on steep slopes in many nearby places. Except for a thrust displacement of less than an inch across one shear surface about 100 feet long within the zone (F. Harold Weber, Jr., oral communication), no evidence was observed that slip occurred on the Olive View faults during the San Fernando earthquake. Trenches across the zone of displacement within and outside Juvenile Hall disclosed no evidence of offset lithology in the upper 15 feet of alluvium attributable to slip on a fault. Survey data indicate that there has been net relative displacement of a few inches in the vicinity of the Juvenile Hall and Converter Station outside of the displacement zone (Youd, 1972). This movement may be related to displacements across faults in the underlying rock during the earthquake of February 9. It is our opinion, however, that tectonic slip, if any, on the Olive View faults was minor and did not influence the displacement of the ground at Juvenile Hall.

Our investigation indicates that ground displacement under future seismic conditions can be expected to remain confined to the zone of displacement that developed during the San Fernando earthquake. This conclusion is based on the lateral extent of the soft soils responsible for the movement and on geologic evidence that past displacement has occurred along this same zone.

CONCLUSIONS

1. Permanent ground displacement in the vicinity of Juvenile Hall and the Converter Station was the result of settlement and gradual migration of soft soil downslope in a narrow zone during the earthquake.
2. The zone owes its displacement to the combined effects of deposition of soft alluvium in a bedrock depression, coalescing alluvial fans, and the presence of near-surface ground water.
3. While it is likely that local liquefaction of soils in the displaced zone took place, soils with liquefaction potential are not sufficiently widespread throughout the zone to account for the lack of stability during the earthquake.
4. Tectonic slip on faults in the vicinity could not be demonstrated as a cause of the displacement.
5. Past displacements of a similar nature have occurred in the area and additional displacements, with characteristics similar to those of February 9, 1971, may be expected in future earthquakes.

CHAPTER 13

History and Data of Crustal Movement Investigations in California[1]

by Roger W. Greensfelder[2]

Crustal movement occurs in two basic forms: 1) fault slip, which may take place either through brittle fracture, causing an earthquake, or as aseismic plastic flow, called "creep"; 2) distortion or strain (see glossary) which may be distributed over a region many miles wide. We are chiefly concerned with aseismic fault slip and fault-related strain in this discussion.

Visible fault rupture accompanying an earthquake was apparently first recognized in 1819 after the Cutch, India, earthquake (Richter, 1958, p. 189). Since that time, surface faulting has been reported on most continents, most notably in western North America, Japan, New Zealand, and Turkey (Richter, 1958, p. 200–201). Creep and strain are subtler phenomena than rupture and so were not recognized until recently. The phenomenon of earth strain was recognized first by H. F. Reid (1910, p. 16–28) in his analysis of triangulation data in connection with the great 1906 "San Francisco" earthquake. Fault creep (though not called by that name) was first reported in the literature by T. W. Koch (1933) in connection with the active Buena Vista thrust fault near Taft, Kern County, California, which had caused considerable damage to oil wells and pipelines passing over or through the fault.

Most historic surface faulting in North America has taken place in California and western Nevada (Bonilla, 1967). The earliest unmistakable occurrence of historic surface faulting in California (and the United States for that matter) was in connection with the great Fort Tejon earthquake of 1857, which was accompained by surface rupture on a 225-mile-long segment of the San Andreas fault between Cholame and San Bernardino (figure 1); right lateral offset was perhaps as much as 10 m. However, earlier earthquakes were accompanied by ground breakage of an unspecified nature: in 1836 on the Hayward fault; in 1838 on the San Andreas fault, San Francisco peninsula; and in 1852 on the Big Pine fault. Since 1857, surface rupture has been reported for 19 earthquakes in California (figure 1), the most recent being that which accompanied the San Fernando earthquake.

Although, in its most general sense, the term "crustal movement" includes short-period motions caused by the passage of seismic waves, this discussion is limited to permanent and ultra-long period (greater than 1 year) deformations. Such deformations are not always closely associated with seismic energy release, but certainly interest in earthquake prediction is chiefly responsible for recently increased efforts to monitor crustal movement. In regard to earthquake prediction, the measurement of long-term strain rates, as well as short-term precursory strain events, is of particular importance.

Geodetic triangulation (see glossary) following the 1906 earthquake provided the first instrumental measurements of crustal displacements, and until very recently triangulation was the only instrumental method employed for that purpose. In the late 1950s, precise electro-optical distance ranging, capable of much greater accuracy than triangulation, came into use; and it is only within the last 6 years that continuous recording of fault slip, strain, and tilt has been employed specifically to study aseismic crustal movement and earthquakes. All of these are discussed below.

GEODETIC AND LOCAL SURVEYS

Geodetic Triangulation

Instrumental measurement of crustal movement in California began in 1906, when the U.S. Coast and Geodetic Survey reobserved their primary trangulation network in the San Francisco Bay region, which had been set up during the years 1851 to 1887. The 1906–07 resurvey revealed that right-lateral displacement, which occurred at the time of the 1906 "San Francisco" earthquake, decreased with distance from the San Andreas fault. These data were thoroughly analyzed by H. F. Reid (1910, p. 16–28) and provided the basis for his elastic rebound theory of earthquake generation. The primary net was reobserved in 1922, and the results of this and the 1906–07 resurvey formed the basis for a systematic program of special-pattern surveys to measure horizontal movement along the San Andreas fault. These have been described by Meade (Meade and Small, 1966; Meade, 1963, 1968, 1970), and their locations and data are briefly summarized here in table 1 and figure 2.

Local Triangulation

Creep on the San Andreas fault was discovered in 1956 when Steinbrugge and Zacher (1960) investigated damage at the Taylor (also called "Almaden" or "Cienega") Winery, which sits directly astride the fault about 7 miles south of Hollister. Reinforced concrete walls and concrete slab floors had been cracked,

[1] Manuscript submitted for publication December 30, 1971.

[2] Seismologist, California Division of Mines and Geology, Sacramento.

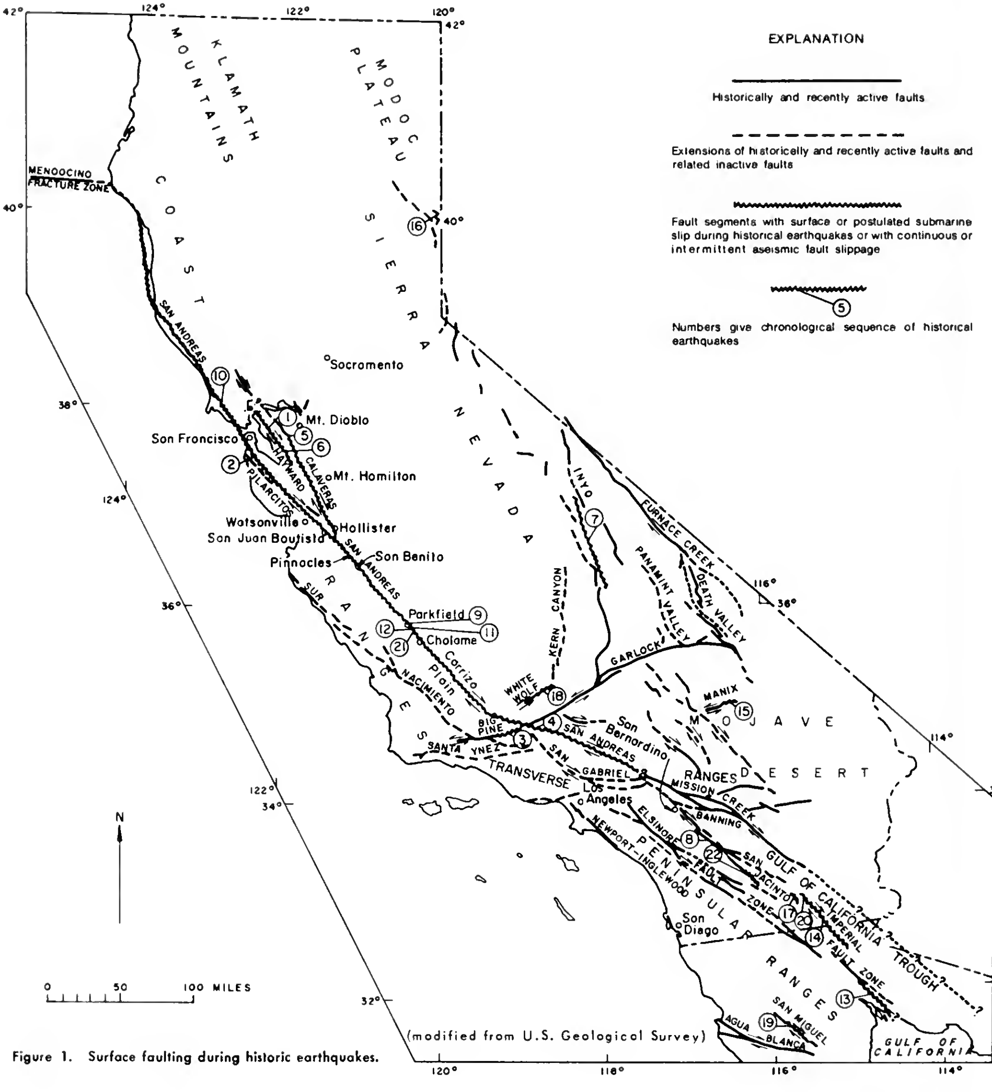


Figure 1. Surface faulting during historic earthquakes.

and progressive deformation had thrown some columns so far out of plumb that they had been rebuilt in 1954. Subsequently, the U.S. Coast and Geodetic Survey set up a small quadrilateral figure across the fault on the north side of the winery. It has been resurveyed annually since 1957; results show that creep movement averages 1.5 cm/yr (Meade, 1966, p. 387). The first creep recorder, which was installed in the winery in 1957 (Tocher, 1960), has indicated an average rate of displacement of 1.3 cm/yr.

In 1960, creep was reported on the Hayward fault by Cluff and Steinbrugge (Radbruch *et al.*, 1966, p. 8–12), who found a building damaged by right-lateral movement on the fault. Since then, right-lateral offset of culverts, sidewalks, railroad tracks, and other structures has been found all along the Hayward fault between Berkeley and Fremont (Radbruch *et al.*, 1966).

Because it was recognized in the early 1960s that creep could be a major hazard to engineering structures, the California Department of Water Resources

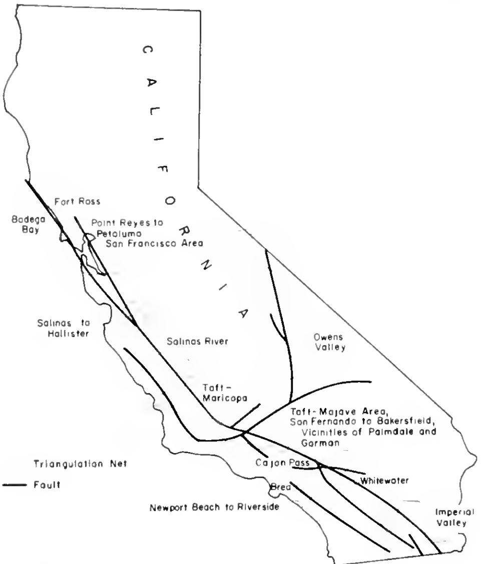
Table 1. Locations and data of triangulation nets for crustal movement studies by the National Ocean Survey (formerly U.S. Coast and Geodetic Survey)

Location (vicinity)	Dates of surveys	Generalized results
Fort Ross	1876, 1906, 1969	No slip on San Andreas fault since 1906; right lateral strain accumulation about 1 ppm/yr.*[1].
Bodega Bay	1968, 1969	No significant change (also measured trilaterally)[1].
Pt. Reyes to Petaluma	1930, 1938, 1948, 1960	Right lateral movement about 1 cm/yr. near San Andreas fault[2]; appears to be strain, not slip.
San Francisco Bay Area	1882, 1906, 1922, 1945, 1951, 1957, 1963, 1969	Right lateral displacement 5 to 6 cm/yr. between Mt. Diablo and San Francisco Peninsula[2]; both fault slip and strain.
Salinas to Hollister	1930, 1951, 1961	Right lateral slip 1.6 cm/yr. on San Andreas fault[2]; total shift across network about 2.6 cm/yr.[3]
Salinas River	1944, 1963	Right lateral slip 3 cm/yr. on San Andreas fault[2].
San Luis Obispo to Avenal	1932, 1951, 1962, 1966	Right lateral slip 15 cm for 1932–51 on San Andreas fault; none for 1951–62; total right lateral shift across network 1.5 cm/yr. during 1932–51[3].
Taft to Maricopa	1943, 1959	Compression 2–3 cm/yr. across Buena Vista thrust fault[4].
San Fernando to Bakersfield	1932, 1952–53, 1963	Data of marginal significance[4, 5].
Taft-Mojave	1959–60, 1967–68	Strain rates approximately 1 ppm/yr., with shear strain paralleling San Andreas fault west of Gorman; east of Gorman, strain axes have scattered orientations[6].
Imperial Valley	1935, 1941, 1954, 1967	Regional right lateral displacement 8.5 cm/yr. during 1941–67[7]; right lateral shear strain about 50 ppm parallel to Imperial fault during 1941–67[8].
Owens Valley	1935, 1956	No significant movement detected.[4]
Gorman	1938, 1949, 1966	No significant movement detected.[9]
Palmdale	1938, 1947, 1958	No significant movement detected.[4]
Cajon Pass	1949, 1963	No significant movement detected.[2]
Brea	1938, 1949, 1966	No significant movement detected.[10]
Newport Beach to Riverside	1929, 1933, 1953	No significant movement detected.[4]
Whitewater	1931 (part), 1950	No significant movement detected.[10]

* "ppm" is short for "parts per million" or "millionths"; strain is stated in fractional change of length; here in parts per million.
[1] Meade, 1970
[2] Meade and Small, 1966
[3] Burford, 1967
[4] Meade, 1963
[5] Miller *et al.* 1969b
[6] Miller *et al.* 1969a
[7] Scholz and Fitch, 1969
[8] Miller *et al.* 1970
[9] Meade, 1968
[10] Meade, 1971, personal communication

supported the U.S. Coast and Geodetic Survey in a cooperative effort to detect creep at locations where the California Aqueduct would cross active faults. In 1964 and 1965 small quadrilateral figures (several hundred meters across) were set up at 21 aqueduct-fault crossing sites (figure 3). Most have been resurveyed annually or biannually since then. The sites are on the San Andreas, Hayward, Calaveras, Sunol, Pleasanton, Nacimiento, White Wolf, San Jacinto, and Cleghorn faults. Creep has been measured at sites on the first five faults named above in the greater San Francisco Bay region. At the other crossing sites, measurements lie within the range of probable error.

Beginning in 1966, the Seismological Laboratory of the California Institute of Technology established a number of fault-crossing angulation nets with a maximum dimension of about 400 m. In these nets, lateral-fault displacement is determined by monitoring angular changes between lines radiating from a point on one side of the fault to several points on the other. These nets, now about 38 in number, are chiefly in southern California south of the Transverse Ranges and on the San Andreas, San Jacinto, Coyote Creek, and Imperial faults; there are also several on the central San Andreas fault (Clarence Allen, 1971, personal communication) (see figure 1 for fault location). Nets on the central San Andreas fault have been surveyed as many as 40 times; on the Imperial and Coyote Creek faults, 12 times; and on others, from one to nine times. In the Imperial Valley region, Hileman *et al.* (1971) reported: "definite or suspected movements have been observed along parts of the San Jacinto, Coyote Creek, Superstition Hills, Imperial, and San Andreas faults; no movement has been detected along the Elsinore and Superstition Mountain faults or along the San Andreas-Banning-Mission Creek fault system northwest of Mecca Hills".



(courtesy of N.O.A.A.)

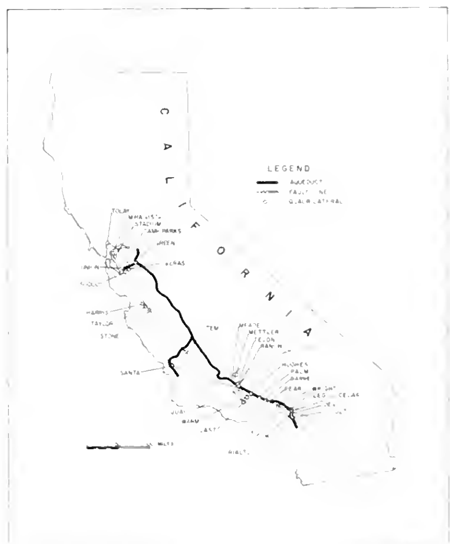
Figure 2. Triangulation nets for crustal movement studies.

Electro-Optical Distance Ranging

When construction of facilities of the California State Water Project began in the late 1950s, the Department of Water Resources' Consulting Board for Earthquake Analysis recommended a program to measure rates of crustal movement in the neighborhood of active faults. Survey lines crisscrossing faults of the San Andreas system from San Francisco to Palm Springs were established (figure 4). The work consisted almost entirely of repeated measurements of the lengths of these lines by Geodimeter (see glossary). Progress of the project to early 1968 has been described by Hoffman *et al.* (1968). In 1968, the California Division of Mines and Geology assumed responsibility for the geodimeter program and considerably augmented the original survey scheme, adding a number of closed figures as well as "crisscross" lines (Greensfelder and Crice, 1971, p. 109).

Distances can be determined by geodimeter to an accuracy of about ten times that of first-order triangulation, which is normally accurate to about 10 ppm (see glossary). This means that crustal movement can be detected in one-tenth the time period (reobservation interval) required by triangulation methods.

Measurements on more than 100 lines have been made annually or as frequently as possible since 1959. Most of these lines cross faults at angles smaller than 30 degrees and are therefore particularly useful for detecting strike-slip movement. In the following discussion, the term "movement" is used in describing the geodimeter data, because these data actually express the combined displacements attributable to both fault slip (creep or earthquake-slip) and strain in the near-fault region. Other data must be examined to distinguish the portion of total displacement due to creep from the portion connected with strain. Comparison of geodimeter measurements with those obtained from creepmeters and alignment arrays (discussed below) shows that long-term (10 or more years) change in



(courtesy of N.O.A.A.)

Figure 3. Quadrilaterals at aqueduct-fault crossing sites.

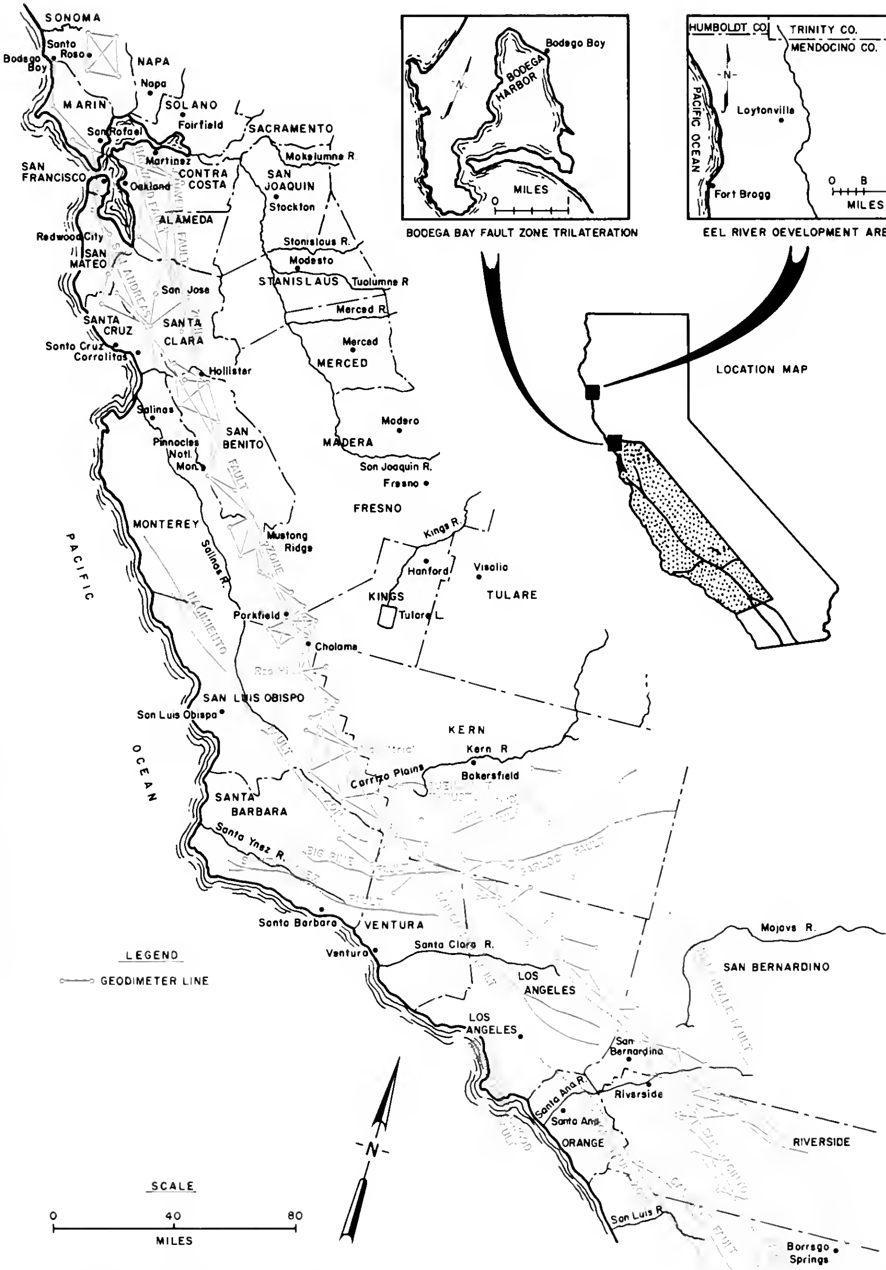


Figure 4. Geodimeter fault-monitoring program.

line lengths is much greater where fault creep occurs than where it does not. In other words, in the zone—generally about 10 km wide and centered on a fault trace—occupied by the geodimeter lines, displacement of points on one side of the fault trace relative to points on the other, and hence the change in length of lines connecting those opposing points, is much greater where fault slip occurs than where it does not, over a period of 10 or so years. If below some depth, perhaps about 20 km, tectonic plates are moving more or less as rigid units, then the above results imply that, where faults are "locked" (that is, not creeping), significant strain must be accumulating outside the zone crossed by the geodimeter lines.

The greatest average movement rates detected over the past decade were along the San Andreas fault between the Pinnacles and Parkfield. In this region, movement has been relatively uniform at a rate of about 3 to 3½ cm/yr. Beyond this segment of the fault, movement dies off to essentially zero near Watsonville on the north and near Cholame on the south (figure 4).

Geodimeter lines crossing the Hayward fault indicate right-lateral movement averaging 1½ cm/yr, and comparable motion appears on the Calaveras fault south of its junction with the Hayward fault about 6 miles south of Mt. Hamilton. North of this point, however, movement on the Calaveras fault dies off to near zero between Mt. Hamilton and Mt. Diablo. Thus it appears that some movement on the San Andreas fault south of Hollister is transferred to the Calaveras fault, and this in turn is shifted to the Hayward fault.

In the Santa Clara Valley and Hollister region and in the Cholame Valley area, the lengths of the geodimeter lines have changed in an erratic fashion. These changes, however, can be correlated with local earthquakes (Hoffman *et al.*, 1968; Greensfelder and Crice, 1971). Along the Carrizo Plain-San Bernardino segment of the San Andreas fault, the data indicate no fault slip and only slight strain accumulation; the strain is observed in the San Bernardino region, across the San Andreas and San Jacinto fault zones, and takes the form of north-south compression at a rate of around ½ ppm/yr (Hoffman *et al.*, 1968, p. 69).

In a recent review of the data gathered by the State's geodimeter program, the California Division of Mines and Geology has found strong evidence for a cyclical variation of dilatational (see glossary) strain with amplitude of 2 to 3 ppm and period of 7 to 8 years. This effect appears to be synchronous from San Francisco to San Bernardino, and appears as a periodic change of length on many lines. Because of the relative infrequency of observation, the effect is clearly discernible only on lines which are not disturbed by the much larger effect of fault slip.

Other organizations have begun to apply electro-optical ranging to the measurement of crustal movement. The National Center for Earthquake Research of the U.S. Geological Survey began its monitoring program in 1965 and by 1970 had established eight small nets from the San Francisco Bay Area to the Hollister region: seven across the San Andreas fault and one across the Calaveras fault. Until recently four of these were monitored fortnightly, and the others, annually. In 1970, the NCER triangulated and trilaterated (see glossary) most of the Salinas-Hollister network, which the U.S. Coast and Geodetic Survey triangulated in 1930, 1951, and 1962. The 1970 data are consistent with those of the earlier surveys, indicating continued combined right-lateral motion of 2½ cm/yr across the San Andreas, Sargent, and Calaveras faults. In 1971, this network was extended to Gilroy.

In 1969 the National Ocean Survey, formerly the U.S. Coast and Geodetic Survey, began trilateration using a geodimeter when a special purpose survey was set up in the Anza-Borrego Desert area, in connection with the 1968 Borrego Mountain earthquake. In the same year, the National Ocean Survey trilaterated the Fort Ross net and established a trilateration net in the Bodega Bay area. In 1970, a trilateration net was established in the Stone Canyon area, about 16 miles southeast of Hollister.

The Geology Department of the University of California, Santa Barbara, established a trilateration net across the Santa Barbara Channel, an area of high seismicity, in 1970–71. This net will probably be remeasured in about 5 years. In 1970, the Department of Geological Sciences at the University of California, Riverside, in cooperation with Imperial College, London, set up a long trilateration arc (see glossary) across the Imperial fault; the arc was remeasured twice in 1971, but results have not yet been published.

Leveling

The U.S. Coast and Geodetic Survey began leveling work in California in 1906, and about 30,000 miles of first-order and 20,000 miles of second-order leveling and releveling had been completed by 1966 (Meade and Small, 1966, p. 390). The most intensive releveling has been and continues to be in the San Joaquin Valley area, where rapid subsidence due largely to ground water withdrawal poses a continuing hazard to the operation of hydraulic systems, particularly the California Aqueduct. There has been more than 22 feet of subsidence at one place in the San Joaquin Valley (Meade and Small, 1966, p. 390).

In 1935, five level lines were established across the San Andreas fault between the vicinity of Maricopa and the San Jacinto Mountains, each of which had been releveled from two to eight times by 1966 (Meade and Small, 1966, p. 391). These and other level data have generally been insufficiently analyzed to allow the drawing of conclusions concerning vertical tectonic movements. However, on the basis of releveling between Mettler in the southern San Joaquin Valley and Gorman in the Tehachapi Mountains, Lofgren (1966) concluded that uplift accompanying the 1952 Kern County earthquake reached a maximum of nearly 2 feet in the Wheeler Ridge area. He also concluded that vertical tectonic movement has continued in the Tehachapi Mountains since 1952. This continuing movement has an east-west axis of flexure about 2 miles south of Grapevine; however, absolute vertical movement is unknown.

Several short level lines were set up across the San Andreas fault on the San Francisco Peninsula by the National Center for Earthquake Research in 1968. In 1969, the center established several "tilt arrays"—actually very small leveling arrays—on the Calaveras, San Andreas, and Coyote Creek faults. The Geology Department of the University of California, Santa Barbara, set up seven fault-crossing level lines in the vicinity of Santa Barbara and four such lines in Death Valley in 1970. Significant vertical movement has not been reported on any of these.

ALIGNMENT ARRAYS AND CREEPMETERS

Since 1964, about 60 creepmeters (see glossary) and 58 alignment arrays (see glossary) have been put into operation by the Earthquake Mechanism Laboratory of the National Oceanic and Atmospheric Administration and the National Center for Earthquake Research of the U.S. Geological Survey. Most of these are located on the San Andreas and Hayward faults. Creepmeters and alignments are frequently located at the same sites, in order to determine what fraction of fault slip is recorded by the creepmeters.

Data from alignment arrays indicate that most fault displacement occurs in a zone less than 6 m wide at most sites (Raleigh and Burford, 1969, p. 380). Creepmeters have shown that fault creep is episodic at most sites, the episodes being called creep events, and that these are not simultaneous at different sites but propagate along the fault at apparent rates of less than 10 km/day; most creep events involve fault segments from several to 20 km long (Nason, 1971, p. 31).

Creepmeters, alignment arrays, and offset structures show that the maximum slip-rate on the San Andreas fault has been about 2.5 cm/yr over the last 60 years, and occurs on the segment between Bear Valley, north of San Benito, and Middle Mountain, north of Parkfield, a distance of about 90 km (see figure 1 for locations). Northward from Bear Valley, total slip since 1906 dies out to zero apparently near Watsonville (Nason, 1971, p. 12); southward from Middle Mountain, total slip for the last 40 years drops to zero a short distance south of Cholame (Brown and Wallace, 1968, p. 30–33). Slippage on the most active central segment is predominantly aseismic; however, a significant fraction of slippage on the end-segments may have occurred during moderate-magnitude ($M = 4$–6) earthquakes. The fact that the crustal movement rate determined from triangulation and geodimeter measurements along the Bear Valley-Middle Mountain segment is ½ to 1 cm/yr greater than the creep rate suggests that right lateral strain is accumulating there.

Active slippage has been observed all along the Hayward fault, from San Pablo to Fremont, at rates of 0.5 to 0.7 cm/yr. On the Calaveras fault, slippage decreases from 1.2 cm/yr at Anderson Reservoir (20 km south of Mt. Hamilton) to 0.6 cm/yr in Hollister; north of Mt. Hamilton, little, if any, slip is occurring (Nason, 1971, p. 14–16).

STRAIN METERS

The quartz-rod strain meter (see glossary) was designed by Hugo Benioff (1959, p. 1019–1032) for secular (that is, long-term trend), tidal, and seismic strain measurements. This instrument was first installed at Dalton, about 33 km NW of Pasadena, in 1953; since then, similar instruments have been installed at Mt. Palomar (1954), Lake Isabella (1957), and Pasadena (1959). These instruments have an intrinsic strain sensitivity approaching 10^{-10}; however, *useful* sensitivity in the ultra-long period range, from 1 day to 1 year and greater, is limited to approximately 10^{-7} by background noise caused chiefly by thermally and barometrically induced strains, both in the ground and directly in the instrument, as well as by fluctuations in ground water levels.

A quartz-rod strain meter was installed in 1967 at Earthquake Mechanism Laboratory's Stone Canyon Observatory 30 km south of Hollister. The Seismographic Station of the University of California, Berkeley, established its San Andreas Geophysical Observatory on the Harris Ranch about a mile north of the Almaden Winery in 1968; a quartz-rod strain meter is included in its complement of instruments.

The Institute of Geophysics and Planetary Physics of the University of California, San Diego, has designed, built, and recently installed two laser-interferometer strain meters which operate over an 800-meter base above ground level. These instruments have a sensitivity of 10^{-10}, and flat response from 0 to 1 megacycle/second. One of the strain meters is located at Camp Elliot, near San Diego; and the other, at Pinyon Flat, in the Santa Rosa Mountains.

The instruments described above have not yet provided significant information on secular strain changes, although they have been quite useful in the study of very long-period surface waves.

TILTMETERS

Seven "permanent" tiltmeter (see glossary) stations are currently in operation in California. The first was installed at Lake Isabella in 1964 by the California Institute of Technology; the Earthquake Mechanism Laboratory installed a tiltmeter at Stone Canyon in 1966 and more recently, installed a similar instrument near the Buena Vista fault. During 1969–71, the National Center for Earthquake Research installed four two-component mercury tiltmeters: at San Francisco, Berkeley, Mt. Hamilton, and Fremont Peak (13 km southwest of Hollister).

Anomalous tilt events have been observed prior to earthquakes in Japan, where tiltmeters have been operated for many years. Rapid accelerations in ground tilting, beginning several hours before earthquakes of magnitude 4½+, were observed during the 1966 Matsushiro earthquake swarm (Hagiwara and Rikitake, 1967, p. 765).

The Danville earthquakes ($M = 4.0$) of June 11 and 12, 1970, located on the Calaveras fault zone about 25 km east of Oakland, were preceded by tilting which began 29 hours before the first shock as recorded on the Berkeley and San Francisco Presidio instruments operated by the National Center for Earthquake Research (Wood *et al.*, 1971). At −29 hours, the tilt-vector on the Berkeley instrument, which had been pointing down and parallel to the Hayward fault, began to swing around toward the Danville earthquakes' epicenter. By −13 hours, the vector had "locked" in the direction of the epicenter, where it remained until after the second shock, when it swung back parallel to the fault, but now 180 degrees from its initial azimuth. These data suggest that tiltmeters may be a key element in an earthquake warning system.

EARTHQUAKES AND CRUSTAL MOVEMENT

Accumulation of Strain

Controversy has arisen over the suggestion that fault slip due to creep and small earthquakes in the central portion of the San Andreas fault system (that is, Hollister to Parkfield) acts as an effective "safety valve" preventing the accumulation of strain in that region. In 1968 C. R. Allen (1968, p. 77) hypothesized that strain release on each of five segments of the system is characterized by one of two basic modes of seismic and creep behavior. One mode shows frequent small-to-large earthquakes (up to Richter magnitude 7½) and creep and is common to the northern, central, and southern "active" areas (figure 5); the other mode is characterized by infrequent great earthquakes (magnitude 8+), few small-to-large shocks, and no measurable creep and is common to the 200-plus-mile segments which ruptured during the great 1857 (Fort Tejon) and 1906 (San Francisco) earthquakes.

In analyzing geodimeter and triangulation data, Scholz and Fitch (1969, p. 6663) concluded that strain is accumulating everywhere along the San Andreas

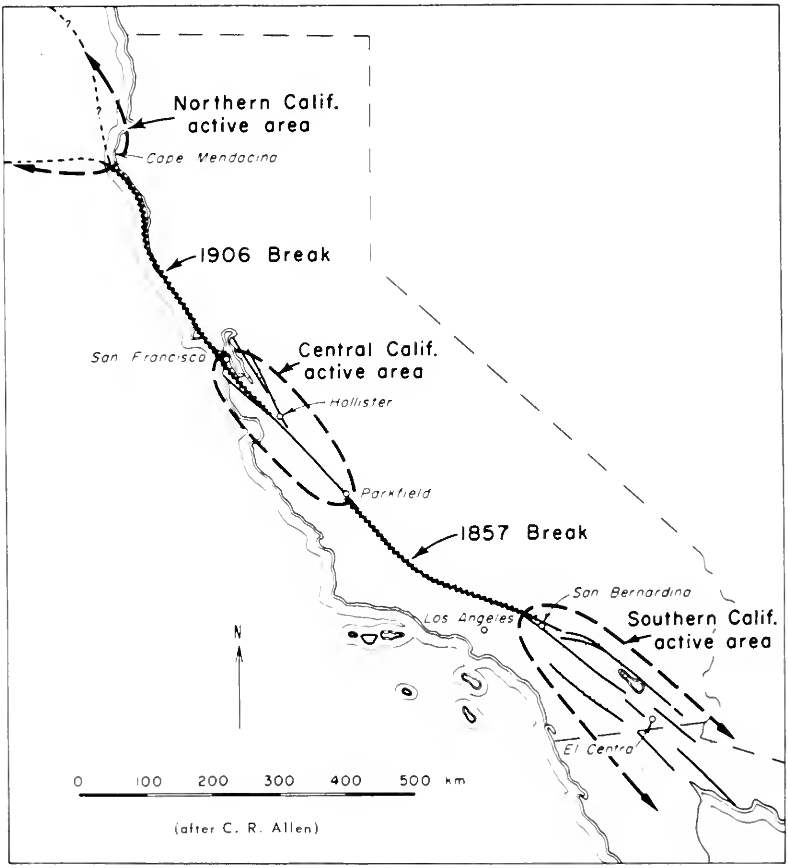


Figure 5. Areas of contrasting seismic behavior.

fault at a rate of about 1 ppm/yr and that fault slip due to creep and minor seismicity "do not release an appreciable amount of the accumulating strain and hence do not serve as a safety valve to prevent major earthquakes as Allen (1968) has suggested." In a later paper the same authors (Scholz and Fitch, 1970) find that *measured* creep on the San Andreas, Hayward, and Calaveras faults can account for only one-third of the geodimeter line changes in the San Francisco Bay Area-to-San Benito region; and, if there is no undetected creep, then principal strain rates must be about ½ ppm/yr. They then explore the possibility that *undetected* creep on minor faults can explain the geodimeter data. By postulating undetected creep at rates of 1.0, 1.0, and 2.0 cm/yr on the Sargent, Silver Creek, and Paicines faults respectively and assuming that creep on all faults extends to great depth (perhaps 100 km), the geodimeter results can be accounted for with no accumulation of strain. Scholz and Fitch (1970, p. 4447) point out that measurements of creep on these minor faults must be made before we can predict seismic risk in the region.

Savage and Burford (1970) have made a thorough analytical review of triangulation data from five tectonically active areas of California: Hollister, Cholame, Santa Barbara Channel, Owens Valley, and Imperial Valley. They found no evidence for strain accumulation in the Hollister, Santa Barbara Channel, and Owens Valley areas for the periods 1930–62, 1880–1923, and 1934–56 respectively. Near Cholame, accumulation of shear strain along the San Andreas fault from 1932 to 1962 appears to have been directly caused by slip a few miles to the north accompanying the 1934 Parkfield earthquake; no significant strain accumulation occurred there from 1951 to 1962. In Imperial Valley, however, they found an average accumulation of 0.4 ppm/yr right-lateral shear strain parallel to the Imperial fault and extending over a zone perhaps 100 km wide.

In their recent discussion of Scholz and Fitch's work (1969, 1970), Savage and Burford (1971) reiterated their view that fault slip accounts for the geodetic observations of crustal movement on the San Andreas fault between San Juan Bautista and Cholame. They cite both recent fault-creep observations and apparent rigid behavior of the crustal blocks flanking this section of the fault. Similarly, they show that the geodimeter lines crossing the Hayward and Calaveras faults are compatible with right-lateral movement at the higher creep rates recently observed on these faults. In the San Francisco Bay Area, the geodimeter and triangulation data do not prove that strain is accumulating there; according to Savage (1971, p. 815), ". . . sensible strain accumulation obtains only within a zone extending a few kilometers on either side of the major faults, and, consequently, strain accumulation is not easily distinguished from fault creep." Nason (1971, p. 191) concurred in these findings, saying that ". . . the geodimeter measurements do not indicate a large elastic strain accumulation of the type suggested by Scholz and Fitch (1969, 1970)."

Earthquake Warning vs. Earthquake Prediction

To "predict" means to tell or declare beforehand; foretell; prophesy. To "warn" means to caution or notify of *possible* danger or risk, and so a warning does not connote the certainty of a prediction. Earthquake prediction may not be possible for many years, because of the many physical parameters which would have to be accurately monitored to provide sufficient information for prediction. These parameters include stress, strain, temperature, water content, and detailed mechanical properties (viscoelastic constants) in and of the rocks at great depths (up to 15 km or more) in the earth's crust. All of these can now be measured on the surface or at shallow depths (up to about 1 or 2 km); however subsurface measurements are extremely expensive and not presently feasible at depths greater than perhaps 5 km. Even an adequate near-surface measurement program would cost many millions of dollars annually.

Earthquake warning, however, may be closer at hand. Field observations, laboratory experiments, and theory all indicate that anomalous earth deformation may be detectable prior to the occurrence of earthquakes, at least shallow-focus earthquakes. In California, data from recently established very dense permanent and temporary seismograph networks have shown that earthquakes occurring in the San Andreas fault system have focal depths no greater than 15 km. This suggests that above 15 km the crust is relatively brittle (assuming earthquakes occur by a process of brittle fracture) while, below that depth, crustal rocks are relatively plastic. Presumably, an earthquake occurs when progressive plastic deformation (creep) in the lower crust loads the brittle upper crust to its breaking strength.

Laboratory experiments in rock mechanics have shown that, under certain conditions, creep in peridotite and dunite may be unstable, and may accelerate in exponential fashion; that is, the creep rate is an exponential function of applied stress (Scholz, 1971, p. IUGG 127). In this fashion, linear accumulation of strain (hence, stress) in the near-fault region at great depth could give rise to accelerating creep on the fault itself. This accelerated creep should be observable at the surface as accelerated strain and tilt.

It is not to be expected that all such accelerated-strain events will be followed by a significant earthquake. Major (1971, p. 154–155) has observed frequent aseismic strain episodes on strain-meter records from the Aleutian Islands, which he associated with creep episodes on a deep shear zone. However, we expect that the proportion of aseismic versus seismic strain episodes varies depending on tectonic regime, and it may be that, in certain regions, all strain episodes with geographic extent and magnitude above some threshold values should be considered as earthquake warnings. Furthermore, experience may show that strain episodes which are short-term precursors of earthquakes have unique characteristics. Hence we feel that earthquake warnings with some useful degree of reliability may be possible on an empirical basis, without thorough and detailed knowledge of all geophysical parameters affecting earthquake occurrence.

GLOSSARY OF TECHNICAL TERMS

Alignment array. An initially straight row of monuments set at right angles across an active fault trace; progressive fault slip is observed by repeated observation of horizontal displacement of these monuments from their initial positions relative to each other.

Arc. A long, narrow triangulation network, generally a chain of quadrilateral survey figures.

Creepmeter. A displacement meter for measuring creep. It actually measures the change in distance between two monuments on opposite sides of a fault trace. Typically, the instrument provides a continuous chart recording of displacements.

Dilatation. A component of plane strain, equal to the change in area per unit area. It may be thought of as an omni-directional extension or contraction.

Geodimeter. "Geodimeter" is the trade name for the most common type of electro-optical distance measuring instrument and is often used generically to denote all such instruments. The instrument is capable of measuring distance with an error less than $\pm$ 1 part per million; this amounts to ± 1 millimeter in 1 kilometer.

Part(s) per million (ppm). One part per million is equal to 1/1,000,000. Fractional error is commonly stated in ppm.

Strain. In its most general sense, strain is the deformation of a body due to stress or force. As used here, strain has the restricted meaning of continuous deformation in a horizontal plane; that is, plane strain. Strain is expressed as a change in length per unit length in a given direction; this quantity is a dimensionless number and is here stated in parts per million (ppm).

Strain meter. An instrument for measuring strain. In geophysical applications, the quartz-rod extensometer is most commonly used. This instrument typically operates over a base 10 to 30 m long and has a sensitivity of .001 part per million or better; it actually measures change in distance between two monuments, the quartz rod serving as a constant-length reference.

Tiltmeter. An instrument to measure change in the attitude or slope of the local ground surface.

Triangulation. The process of measuring the angles necessary to determine precisely the positions of monuments in a trigonometric survey; in this process, the earth's surface is divided into a series of triangles. A transit or theodolite is the instrument used to measure these angles.

Trilateration. The process of measuring the lengths necessary to determine precisely the positions of monuments in a trigonometric survey. An electronic or electro-optical distance ranging instrument, such as a Geodimeter, is normally used in such a survey.

CHAPTER 14

Earth Movements from Geodetic Measurements[1]

by J. C. Savage[2], R. O. Burford[2], and W. T. Kinoshita[2]

The San Fernando earthquake of February 9, 1971, was accompanied by pronounced earth movements in the northern part of San Fernando Valley along the front of the San Gabriel Mountains. Extensive geodetic control existed over a part of this area, and resurveys of that control permit quantitative measure of the deformation produced by the earthquake. Unfortunately, the pre-existing control is confined largely to the southwest quadrant of the zone of deformation. Nevertheless, changes in the horizontal and vertical geodetic control in the region affected by the San Fernando earthquake of February 9, 1971, are consistent with that predicted for a simple dislocation model with the following parameters: fault length along strike 15 km; fault width (measured down dip) 8 km; depth to top of fault 0.75 km; dip 45°N.10°E.; reverse slip 2 m; and left slip 2 m. The maximum deformation (2 m uplift and 2 m left shift) is concentrated just north of the zone of tectonic rupture, and the deformation is reduced to about a quarter of its maximum value within 5 km north of that zone. Deformation south of the zone of tectonic rupture is appreciably smaller (less than 0.1 m subsidence and 0.6 m horizontal displacement). Repeated surveys after the earthquake show that up to 0.4 m of afterslip occurred in the days following the earthquake.

RELATIVE VERTICAL MOVEMENT NEAR THE SURFACE RUPTURES

The general pattern of vertical displacement accompanying the earthquake was derived by comparing postearthquake leveling observations with adjusted elevations based on surveys completed for the most part during the period 1960–63. However, elevations based on 1929 observations provided the only pre-earthquake vertical control available for portions of the San Gabriel Mountains area north of the surface ruptures. The pre-earthquake control was compiled from several different sources, combining the results of different categories of leveling (degrees of resolution or quality) from first down to fourth order. The apparent vertical changes shown in figures 1 and 2 are thus still in a preliminary state, but it is very unlikely that later adjustments will appreciably affect the contour pattern shown in figure 2.

The general features of the vertical movement pattern (figure 2) include abrupt upwarping associated with south-facing scarps over a zone of surface fractures 0.3 to 1.2 km in width, slight downward movement combined with minor northward tilt south of the zone of surface rupture, and pronounced uplift combined with strong northward tilt on the north side of the zone. The maximum uplift just north of the zone of fractures varies between 1 and 2.5 m along distinct segments of the break, and the uplift decreases to about 0.5 m within distances of 2.5 to 4.5 kilometers north of the zone of surface breakage. The vertical movements shown are related to a reference mark on the north side of Hansen Lake which probably moved downward about 0.02 m relative to a tidal bench mark in the San Pedro area.

An interesting feature evident in the contour pattern is the en echelon arrangement of distinct segments of the zone of steep upwarping, corresponding to a similar relationship between the Tujunga and Sylmar segments of the surface break (see figure 1 for the location of those segments). The pattern is stepped to the north as the steep upwarp is traced from east to west, and the maximum uplift at the south edge of the north block seems to decrease abruptly about 1 m at each northward step. The east-west trending axis of maximum uplift from north of the Tujunga segment to north of the Sylmar segment is not noticeably shifted, however. This pattern could be due to transfer of slip within a kilometer or so of the ground surface from a ~ 45° dipping fault plane onto steeper bedding-plane faults, combined with an abrupt decrease in total displacement and a more efficient transfer of slip onto steeper planes on the Sylmar segment.

A north-south oblique-slip tear fault in the hanging-wall block connecting the east end of the Sylmar segment with the west end of the Tujunga segment is postulated on the basis of the pattern of surface faulting and vertical movement. The possible tear fault would have a vertical slip component of perhaps 2 m with the east side up, combined with right-lateral and east-west contractional components of about the same amount. North of the east end of the Sylmar segment, possible displacement across the north-south trend would be at maximum only about half the value estimated above, representing the apparent difference in movement between the blocks north of the Tujunga and Sylmar segments (about 0.7 m difference in uplift, for example). This difference probably dies out to the north; it cannot be documented in the area between the Veterans Administration Hospital and Pacoima Reservoir (figure 2). The tear-fault interpretation is supported by the presence of the north-south trending mountain front and by a diffuse north-south band of surface fractures tending to connect the two main segments. Changes in grade along streets crossing certain of these fractures demonstrate that the east

[1] Publication authorized by the Director, U.S. Geological Survey.

[2] National Center for Earthquake Research, U.S. Geological Survey, Menlo Park, California 94025.

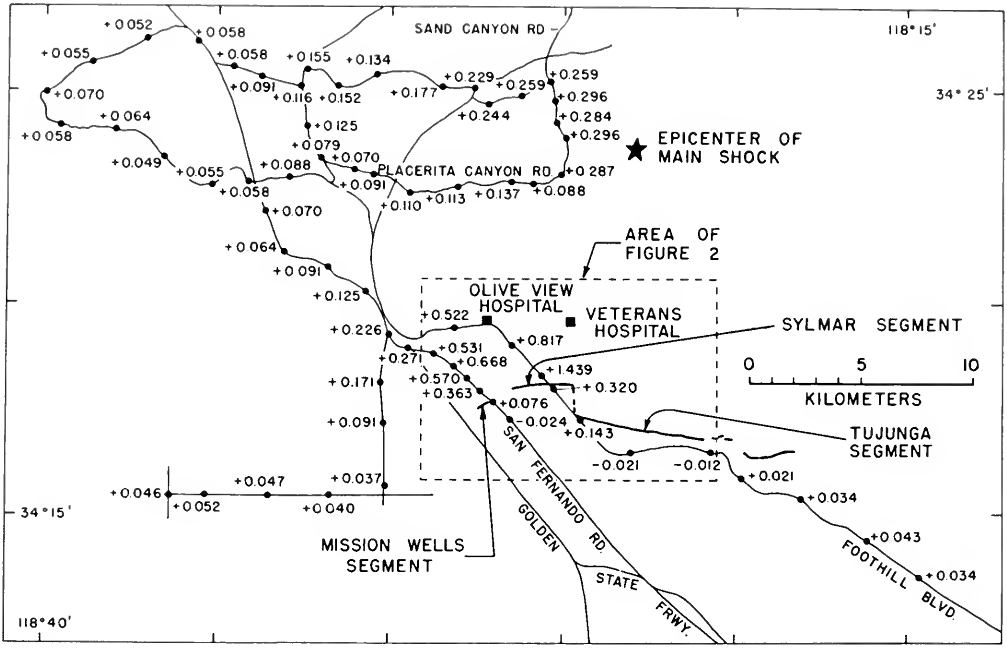


Figure 1. Selected vertical displacement values (in meters) determined at first order bench marks by comparison of postearthquake preliminary elevations with 1970 adjusted elevations (after figure 3 from Geodetic Section—Survey Division, Department of County Engineer, County of Los Angeles, 1971).

side was uplifted about 1.3 m across a portion of the zone of surface disturbance.

The possible northward swing of the 0.5 m contour in the area east of Pacoima Reservoir is probably due to pre-earthquake uplift subsequent to the 1929 leveling along Little Tujunga Canyon combined with uplift associated with the earthquake. A qualitative elastic rebound model illustrated as a set of vertical displacement profiles in figure 3 shows the effect of comparing postearthquake levels with leveling data obtained at various pre-earthquake times. The older the pre-earthquake observation, the more secular uplift due to gradual elastic loading will be included with the changes due to elastic rebound during the earthquake.

Profiles of vertical deformation constructed from the contours along the lines A-A′ and B-B′ shown in figure 2 are presented in parts A and B of figure 4. These profiles illustrate clearly the contrasts in vertical movement and tilt between the north and south blocks as well as the differences in uplift and tilt between the blocks north of the Sylmar and Tujunga segments. The suggestion that the vertical uplift may have been sharply accentuated just north of the zone of surface fractures by transfer of slip onto steeper splay faults off the main slip plane is also illustrated. Asymmetry in vertical deformation across the fault trace is presumably due to lack of constraint on the hanging wall block as the break propagated toward the surface rather than to lack of a downward slip component on the footwall block.

Appreciable vertical uplift along Placerita Canyon Road and Sand Canyon Road in an area about 4 km west of the main-shock epicenter (about 10 km north of the Sylmar segment) was disclosed by comparison of postearthquake unadjusted elevations with pre-earthquake constrained elevations (1970 adjustment) for which the bulk of observations were completed during the period 1963–69 (figure 1). Preliminary values of uplift in the area vary between + 0.110 and + 0.296 m relative to a tidal bench mark in the vicinity of San Pedro. The uplift changes abruptly from about + 0.1 m to about + 0.3 m from west to east at the intersection of the two roads, a possible indication of an upwarp overlying the northwest edge of the buried slip plane. Uplift values from this area are not included on the profiles of observed vertical displacement (profiles A-A′ and B-B′ of figure 4), although a northward extrapolation of the trend in tilt at the north end of profile A-A′ predicts about + 0.25 m for the area.

There is ample evidence that stations quite remote from the epicentral region toward the northwest also were uplifted during the period 1968–1971 by as much as + 0.08 to + 0.11 m (Ellingwood and Williamson,

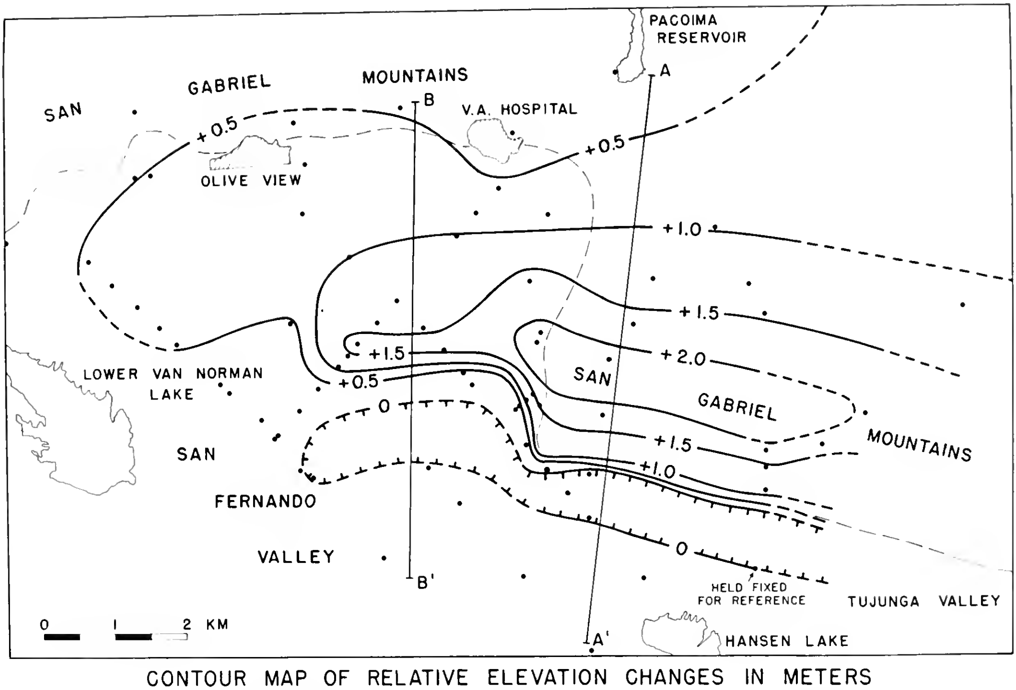


Figure 2. Vertical displacements (in meters) for part of the area surrounding the surface ruptures. Elevation changes relative to a local reference bench mark on the north side of Hansen Lake (BM 5-N-22 on Foothill Boulevard at Eldridge Avenue), which probably moved downward about 0.02 m relative to a tidal bench mark in the San Pedro area, were determined at locations indicated by solid dots. Lines for vertical displacement profiles shown in figure 4 are designated A-A′ and B-B′.

1971, pp. 151–152). These changes are not unusual within the Transverse Ranges Province and suggest that the uplift indicated in Placerita Canyon and Sand Canyon probably cannot be attributed solely to earthquake-associated deformation.

The ~ 350 microradian northward tilt on the surface of the hanging-wall block north of the Sylmar segment of the surface break was confirmed by independent pre- and postearthquake leveling data along the Wilson Drainage Channel between Pacoima Wash Channel and Wilson Debris Basin just north of Olive View Hospital. These data were furnished by the Los Angeles office of the District Engineer, U.S. Army Corps of Engineers.

CHANGES IN HORIZONTAL CONTROL

The area affected by the San Fernando earthquake was covered by a relatively dense network of triangulation most of which was established within a few years of 1935. After the earthquake, 36 lines (figure 5) connecting 16 stations (see table 1 for identification of stations and abbreviations used in this paper) were remeasured using a Geodolite, a precise electro-optical distance-measuring device. A comparison of the two surveys showed that the distances between stations changed as shown in table 2. The accuracy of the distances deduced from the pre-earthquake survey is about 10 ppm. The accuracy of the postearthquake survey is at least an order of magnitude better. Thus, the uncertainty in the changes in line length shown in table 2 should be about 10 ppm.

The zone of tectonic rupture, which presumably represents the fault trace, is also sketched in figure 5. Comparison of figure 5 and table 2 shows that lines which cross the zone of tectonic rupture at a high angle (for example, PL1 to P2, TUJ RM1 to 6P10, SF8 to P2) tend to be shortened by the earthquake, suggesting reverse faulting. Lines which cross the zone of tectonic rupture at low angles and trend NW (for example, 6P10 to PL1) tend to be lengthened, whereas similar lines which trend NE (for example, P2 to TUJ RM1) tend to shorten. These low-angle lines then suggest left-lateral slip on the fault. A more detailed discussion of the horizontal displacements will be given in the following section where comparison can be made with a theoretical model.

There is reason to believe that some of the changes in line lengths may be due to surficial land motions which are not tectonically significant. This is possibly the case at PL1, a station located on a hilltop traversed

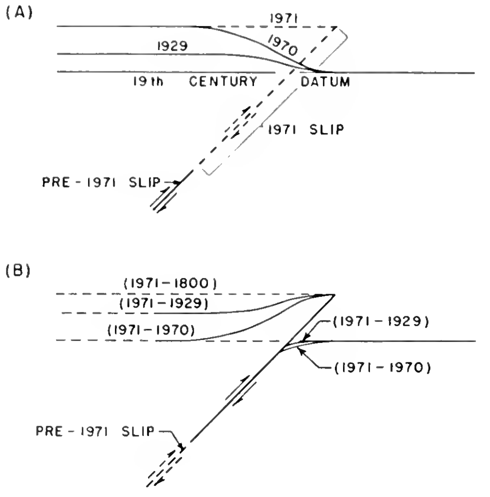


Figure 3. Qualitative elastic rebound model for the earthquake. Part A shows the progressive deformation and rupture of a hypothetical 19th century horizontal datum at sample times 1929, 1970, and post-earthquake 1971. The pre-earthquake deformation is associated with slip on the deepest sections of the fault (the solid fault line which extends to indeterminate depth in the figure). The sudden deformation at the time of the earthquake is associated with rupture of the hitherto locked section of the fault (dashed fault line in figure). Part B shows qualitative results of the comparisons of postearthquake leveling with elevations determined in 1929 and 1970.

by large cracks. These cracks are clearly associated with down-slope movements of large masses of earth, but because of the complexity of the crack distribution, it is not possible to be certain of the direction in which the hilltop was carried, if indeed it was moved. A second example is station MESA located on the south end of a ridge which breaks off sharply to the south into the San Fernando Valley. Several large east-west cracks cut the ridge within 100 m north of the station suggesting down-slope motion to the south. Landslide motion near PL1 and MESA has been mapped by Morton (1971; see his figures 4A and 4B), but those slides would not have shifted the station marks. The ground near station MAYS 2 also exhibited many small cracks, and minor surficial movement is possible there. No obvious evidence of appreciable surficial movement was detected at the other stations.

As can be seen in figure 5, the postearthquake surveys do not control the position of station EAST. We have used the postearthquake measurements of the National Geodetic Survey to calculate changes for two additional lines, EAST to MISSION (shortened .08m) and EAST to MAY (shortened .10m), which, together with the line PE2 to EAST, control that position.

Almost all of the pre-earthquake data were based on surveys completed in the period 1930–40. Three stations were surveyed later. Of these one (PE2) was merely an eccentric set-up tied to a 1935-survey sta-

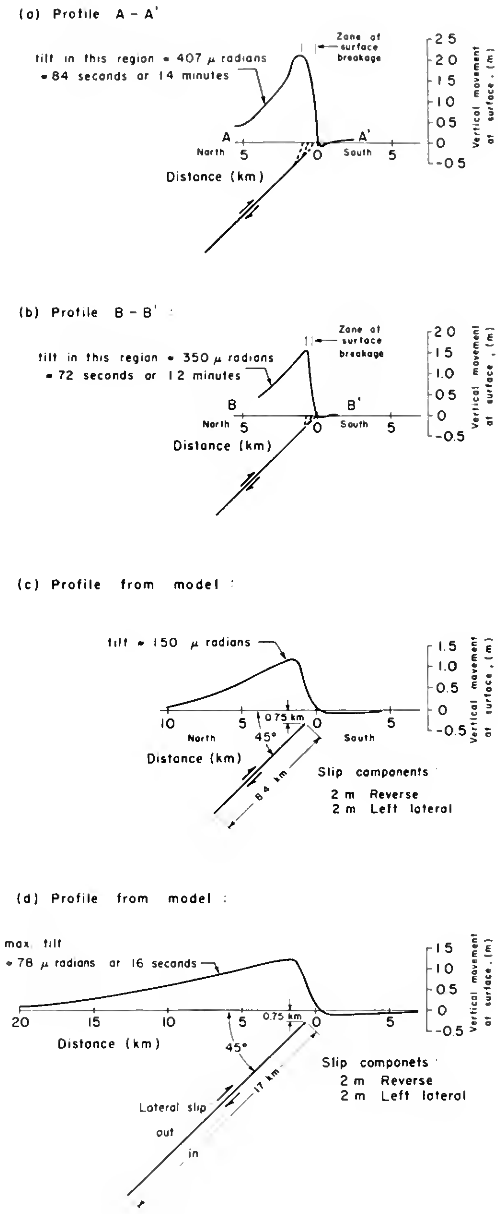


Figure 4. Profiles of observed and theoretical vertical displacements. Parts A and B show vertical displacements along lines A-A' and B-B' indicated in figure 2. Parts C and D show vertical displacements predicted by two dislocation models studied.

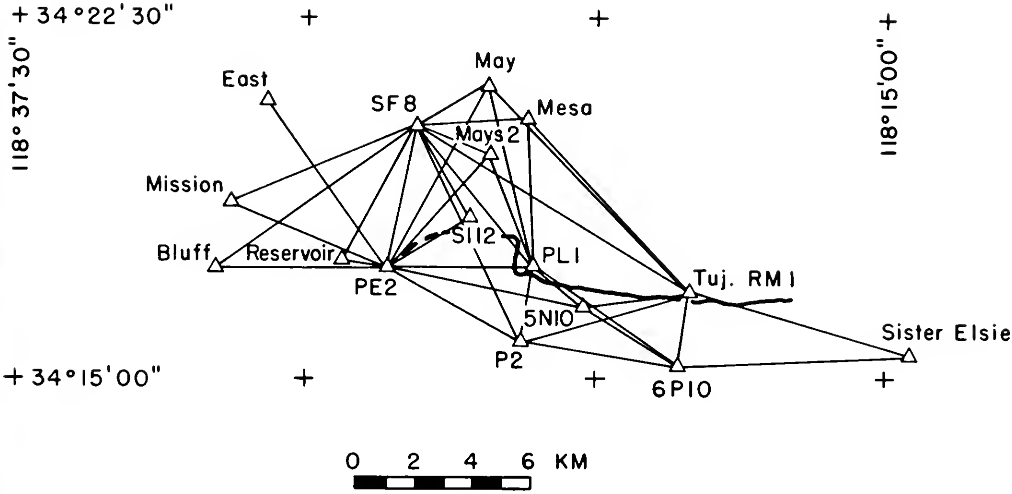


Figure 5. Trilateration network observed in 1971 to study horizontal displacements. The lengths of the lines shown were all measured by Geodolite. The heavy sinuous line running from near PE2 past SI 12, PL1, and TUJ. RM1 represents the San Fernando fault zone shown in figure 1.

tion, and the other two (MESA and MAYS 2) stations were located by triangulation surveys in which the 1935 data were held fixed. Thus, the pre-earthquake surveys generally refer to the position of the stations some 35 years previous to the earthquake. The changes in table 2 may then be somewhat too large, particularly for stations north of the zone of tectonic rupture, because of strain accumulation preceding the earthquake; this is the same phenomenon explained in figure 3 for vertical motions. However, the data available on pre-earthquake strain accumulation (Whitten, 1971) suggest that strain accumulation probably did not exceed the estimated survey error (10 ppm), and thus the effect of pre-earthquake movement after 1935 is not thought to be significant.

Table 1. Horizontal control resurveyed.

Abbreviation	*Station (establishing agency and year)*
PL1	"PACOIMA L1 RE2177" (Los Angeles County, 1935)
PE2	"AQUEDUCT #1 PACOIMA E2 1956 ECC RE2177" (Los Angeles County, 1956)
Mays 2	"MAYS NO. 2 1967" (Metropolitan Water District, 1967)
SF8	"SYLMAR F8 1935 RE2177" (Los Angeles County, 1935)
May	"MAY 1932" (U.S. Coast and Geodetic Survey, 1932)
Mesa	"MESA LBL 1945" (U.S. Forest Service, 1945)
P2	"PACOIMA NO. 2 RE62 1933" (City and County of Los Angeles, 1933)
SI12	"SYLMAR I12 RE2726 1936" (Los Angeles County, 1936)
Reservoir	"RESERVOIR 1932" (U.S. Coast and Geodetic Survey, 1932)
Mission	"MISSION POINT 1932" (U.S. Coast and Geodetic Survey, 1932)
East	"EAST 1932" (U.S. Coast and Geodetic Survey, 1932)
Bluff	"BLUFF 1932" (U.S. Coast and Geodetic Survey, 1932)
6P10	"6 P 10 1940" (City of Los Angeles, 1940)
5N10	"5 N 10 1940" (City of Los Angeles, 1940)
Tuj RM1	"TUJUNGA RM1 CA 1937" (Los Angeles County Flood Control District, 1937)
Sister Elsie	"SISTER ELSIE . . ." (U.S. Geological Survey and Los Angeles County, 1931)

A DISLOCATION MODEL OF FAULTING

The major features of the surface deformation produced by faulting can be approximated by a simple dislocation model in which the fault is represented by a rectangle of arbitrary dip within an elastic half space (figure 6). The displacement field generated by imposing a constant slip across that rectangular surface is readily calculated from algebraic expressions given by Mansinha and Smylie (1971). The advantage of such a representation is that comparison of the observed surface deformation with the calculated deformation allows one to infer the position, attitude, and extent of the fault as well as the slip on the fault.

Figure 6 shows the parameters of fault dip (δ), fault length (2L), fault width (W), and depth to the top of the fault surface (h) needed to describe the fault model. In addition, the position of the origin of coordinates, the dip direction, and two components of slip (dip slip and strike slip) must be specified. Table 3 shows the parameters chosen for the dislocation model employed in this paper. The fault length has been chosen to match the length of the observed zone of surface rupture. The dip was suggested by the distribution of aftershocks. The other parameters were chosen to make the calculated surface deformation approximate the observed deformation. The position of

Table 2. Line-lengths and line-length changes, San Fernando, 1935 and 1971.

Line		*Length* (meters)*		*Change in length (meters)*
Station 1	*Station 2*	*1935 datum*	*1971 (postquake)*	
P2	5N10	2973.43	2973.56	.13
PE2	BLUFF	7256.39	7256.707	.32
PE2	EAST	8116.16	8116.452	.29
PE2	MAY	7572.70	7572.334	−.37
PE2	MAYS2	5454.10	5453.719	−.38
PE2	MISSION	7048.57	7048.978	.41
PE2	P2	5728.76	5728.552	−.21
PE2	RESERVOIR	2420.21	2420.592	.38
PE2	SI12	3150.74	3149.946	−.79
PE2	5N10	7499.54	7499.681	.14
PL1	MAY	6951.26	6949.936	−1.32
PL1	MAYS2	4511.72	4510.475	−1.24
PL1	MESA	5444.05	5442.820	−1.23
PL1	P2	3229.33	3229.226	−.10
PL1	PE2	5141.72	5139.665	−2.06
PL1	SF8	6708.68	6707.098	−1.58
PL1	5N10	2746.70	2748.372	1.67
SF8	BLUFF	9643.56	9643.450	−.11
SF8	MAY	2874.85	2874.638	−.21
SF8	MAYS2	2719.77	2719.620	−.15
SF8	MESA	4406.76	4406.161	−.60
SF8	MISSION	7776.93	7776.907	−.02
SF8	P2	9268.57	9268.301	−.27
SF8	PE2	5354.90	5354.932	.03
SF8	RESERVOIR	5918.50	5918.542	.04
SF8	SI12	4063.59	4063.147	−.44
TUJ RM1	MAY	11732.37	11732.696	.33
TUJ RM1	MESA	9457.79	9458.196	.41
TUJ RM1	P2	7077.35	7076.801	−.55
TUJ RM1	SF8	12711.18	12711.582	.40
TUJ RM1	SISTER ELSIE	8917.12	8917.241	.12
TUJ RM1	5N10	4345.14	4344.648	−.49
6P10	P2	6555.34	6555.306	−.03
6P10	PL1	7405.21	7407.098	1.89
6P10	SISTER ELSIE	9143.96	9144.074	.11
6P10	TUJ RM1	2613.56	2612.586	−.97
6P10	5N10	4665.32	4665.328	.01

* Lengths are distances on Clarke spheroid.
1935 lengths determined by triangulation.
1971 lengths determined by Geodolite (except for P2-5N10, which was determined by triangulation).

the surface projection of the fault surface relative to the mapped zone of tectonic rupture is shown in figure 7A.

Figure 7A shows the changes in elevation predicted by the dislocation model. This calculated deformation can be compared to the observed deformation shown in figures 1 and 2 (notice that figure 2 covers only the stippled area in figure 7A). A north-south profile of elevation changes across the dislocation model is shown in figure 4C; this profile can be compared directly with the observed profiles in figures 4A and 4B. These comparisons show that although the dislocation model reproduces the gross features of the deformation, the details are not well modeled (for example, maximum observed uplift exceeds 2 m, but the maximum predicted uplift is 1.2 m). A better fit could be obtained by increasing the reverse component of slip and also the dip in the dislocation model. However, we have chosen not to make those changes because we believe the discrepancies between observation and model are due to the greater complexity in faulting as the fault plane approaches the free surface. As shown in figures 4A and 4B, subsidiary faults, dipping more steeply than the main fault, are thought to carry the slip from the top of the main thrust plane to the free surface. Geological evidence for these subsidiary faults is cited by Sharp (this Bulletin). The zone of tectonic rupture is then the trace of the subsidiary faults on the free surface. It is clear that such steeply dipping faults will enhance the vertical uplift near the toe of the thrust. The results of a simple dislocation calculation modeling this effect are shown in figure 8, which represents a vertical section perpendicular to the fault strike. We have added to the fault model described in table 3 a

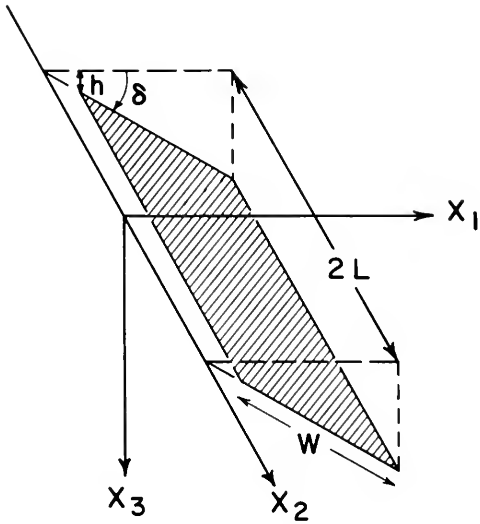


Figure 6. Parameters required to define a dislocation model of a fault. The shaded rectangle represents the fault surface (length 2L, width W) which dips at angle δ in the x_1 direction. The top of the fault is buried a depth h below the free surface (x_1-x_2 plane).

Table 3. Fault parameters employed for dislocation model fit (See figure 7).

dip σ	45° N.10°E.
length 2L	15 km
width W	8.4 km
depth h	0.75 km
dip slip	2 m reverse
strike slip	2 m left
origin of coordinates	0.3 km N. of Pacoima Memorial hospital near mouth of Kagel Canyon (34° 17′ 05″ N., 118° 22′ 50″ W.)

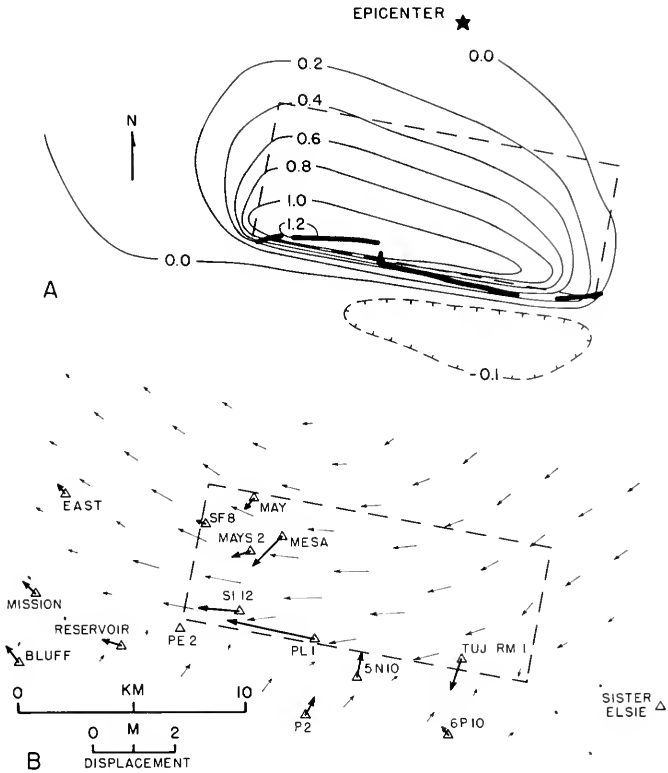


Figure 7. Deformation induced on the free surface by slip on the dislocation model described in table 3. A) The upper figure shows the vertical component of displacement in meters. Values plotted are differences between first observations on each line and subsequent observations (for example, 2-1 is the elevation determined in the second survey less the elevation determined in the first survey). The dashed rectangle is the projection of the fault model upon the free surface. The heavy lines along the south end of that rectangle show the approximate location of the San Fernando fault zone. The shaded rectangle shows the area covered by figure 2. B) The lower figure shows horizontal displacement (light arrows) induced on the free surface by slip on the dislocation model of table 3. The heavy arrows originating at triangles represent the observed displacement at triangulation stations in the area. The dashed rectangle represents the projection of the fault model upon the free surface.

subsidiary fault (dip 65°N. 10°E., width 0.83 km, length 15 km, 2 m reverse slip, 2 m left slip) which joins the top of the main fault to the surface. The effect of the subsidiary fault is to increase the maximum uplift and tilt of the northern block very appreciably. Thus we suggest that the overall fit in figure 7 could be improved by introducing an imbricate structure near the toe of the thrust.

It is reasonable to expect that the focus of the main shock of the San Fernando earthquake would lie on the fault plane. Yet it is clear from figure 7A that our model fault does not fulfill this expectation. In fact, the model fault would have to be almost twice as wide to reach the focus which lies at a depth of about 13 km and at a distance of 13 km N of the zone of tectonic rupture. Figure 4D shows a north-south profile of the vertical deformation expected for a fault of sufficient width to reach the earthquake focus. It is clear that the narrow fault model (figure 4C) is the better fit to the observed deformation; the wider fault model requires a more extensive north-south distribution of vertical deformation. The difficulty that simple fault models yield what are apparently too-narrow fault widths has been encountered before (for example, Savage and Hastie, 1969, p. 1943) and appears to be associated with the restriction that slip on the model-fault plane is constant. It appears more likely that slip decreases down dip along the fault surface, approaching zero slip at the lower end. Inasmuch as the model employed makes no provision for variability in slip with depth, the fault width must be reduced to compensate for the smaller slip at depth.

The survey data (figure 1) indicate an uplift of about 0.25 m occurred roughly 4 km west of the epicenter (just beneath the c in "epicenter" in figure 7A) in the period 1963–71. As was discussed earlier it is not certain how much of this displacement was associated with gradual regional uplift rather than the sudden earthquake movement. The dislocation model described in table 3 yields an uplift of about 0.06 m in this area, and the wider model of figure 4D yields about 0.40 m. Presumably, a dislocation model with variable slip on the fault plane could be designed to account for any intermediate uplift in this area.

Figure 7B shows the horizontal surface displacement predicted by the model fault of table 3. Also shown in that figure are the horizontal displacements of the triangulation stations listed in table 1 as inferred from the differences in the pre-earthquake and postearthquake surveys. Comparison of the two surveys, of

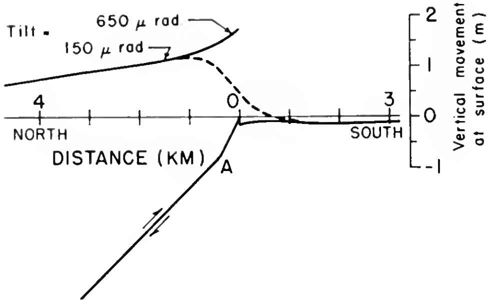


Figure 8. Profile of vertical displacement along a section perpendicular to strike induced by the fault model of table 3 supplemented by a short subsidiary fault (dip 65°, length 15 km, width 0.83 km, 2 m left-lateral and 2 m reverse slip) connecting the top of the main fault (A) to the free surface (O). The dashed line represents the vertical displacement produced by the main fault alone. This example suggests that the details of deformation near the toe of the thrust are dominated by the subsidiary faults.

course, yields only the relative displacements of the stations, and any rigid-body motion (translation and rotation) may be applied to the net as a whole without changing the relative displacements. We have selected the rigid-body motion to give what appears to be the best fit to the displacement field calculated from the dislocation model. This choice turned out to be essentially equivalent to holding the position of SISTER ELSIE and the azimuth SISTER ELSIE to PE2 fixed. We emphasize, however, that this choice was not arbitrary but rather the consequence of a fitting procedure. The displacements calculated from the dislocation model are in qualitative agreement with the displacements inferred from the surveys, but the quantitative fit is not good. The largest discrepancy, that at PL1, may be due in part to surficial down-slope movement at that station as was discussed in the preceding section. However, Burford *et al.* (1971, p. 84) have reported relative horizontal motion of comparable magnitude (2 m) measured from the changes in distances between street intersections across the Sylmar segment of rupture (0.7 km south of SI 12 in figure 7B). Thus, we do not believe the indicated movement at PL1 is necessarily anomalous. We think the most likely explanation for these rather large horizontal motions near the toe of the thrust is that they are produced by subsidiary faults. This explanation, of course, is the same as that advanced for the large vertical motions observed near the toe of the thrust (figure 8). Downslope motions may have affected MESA, though there the discrepancy is not so serious. Uncertainties of as much as 0.2 m in the displacement of the triangulation stations on the western edge of the network relative to those on the eastern edge may have been introduced as the result of accumulation of errors in the pre-earthquake surveys; this may account in part for the anomalously large displacement indicated at BLUFF.

Jungels and Anderson (1971) have reported that discontinuities in the tilt and strain recordings at Isabella (147 km N. of the epicenter) and in strain at the University of California, San Diego, (210 km S.E. of epicenter) occurred at the time of the earthquake. Presumably these discontinuities represent permanent deformation imposed by the earthquake, and consequently the magnitudes of those discontinuities can be compared with the permanent strains and tilts at those localities calculated from the dislocation model of table 3. The comparison is shown in table 4. The agreement is at best order of magnitude only, and in one case (N. 38°W. tilt at Isabella) not even that. The sense of strain (that is, compression rather than tension) calculated from the dislocation model for the N. 52°E. component at Isabella is opposite the observed offset. The significance of the lack of good agreement between the far-field deformation calculated from the dislocation model and actually observed is not clear. The possibility that the far-field observations are distorted by local effects (joints or faults in the neighborhood) cannot be neglected, nor can the possibility that the dislocation model is inadequate in the far field because of the use of a uniform elastic half space to approximate the spherical heterogeneous earth. All that can be said is that the agreement in table 4 is better than has been reported for any earthquake in the past.

Table 4. Comparison of observed far-field deformation with deformation calculated from the dislocation model of table 3.

Component	*Observed deformation*	*Calculated deformation*
Strain[1] (nanostrain)		
Isabella		
N. 52° E.	+ 4.2	− 8.
N. 38° W.	+13.6	+18.
University of California, San Diego		
N. 45° E.	− 1.6	− 2.
Tilt[2] (nanoradians)		
Isabella		
N. 52° E.	< 7	− 6.
N. 38° W.	100	5.
Moment[3] (dyne-cm)	0.8×10^{26}	1.0×10^{26}

[1] Extension taken as positive. Observed data from Jungels and Anderson (1971).
[2] Tilt downward in indicated direction taken as positive. Observed data taken from Jungels and Anderson (1971).
[3] Observed value calculated from seismic radiation by Wyss and Hanks (1972).

Table 4 also shows a comparison of the seismic moment (product of rigidity μ, slip, and fault area) calculated from the low frequency limit of the spectra of seismic body waves radiated from the main shock (Wyss and Hanks, 1972) with the product calculated from the parameters in table 3 with $\mu = 3 \times 10^{11}$ dynes/cm². The agreement here is very satisfactory.

Although the simple dislocation model is not a particularly good fit to the observed deformation, it nevertheless does describe the gross features of a large number of diverse observations. Thus, we believe the dislocation model specified in table 3 is a fair representation of the average properties of the faulting associated with the San Fernando earthquake. We believe a better description would include variability of slip with depth on the fault (for example, double the width of the fault and have slip decrease linearly from the maximum value of 2 m left slip and 2 m reverse slip at upper end to zero at the lower end) and subsidiary faults near the toe of the thrust.

MEASUREMENT OF AFTERSLIP

Continued slip on tectonic fractures has been observed following a number of California earthquakes (Nason, 1969), most recently following the 1966 Parkfield and 1968 Borrego Mountain earthquakes (Wallace and Roth, 1967; Smith and Wyss, 1968; Burford, 1972). The term "afterslip" for this phenomenon has been proposed by Nason (1969, 1971) to emphasize a space-time relationship to aftershocks. Afterslip seems an acceptable term inasmuch as decay in rate of continued slip apparently parallels a similar decay in frequency of aftershocks (Smith and Wyss, 1968), although it has not been conclusively demonstrated that afterslip is generated directly by sudden slips associated with aftershocks (Scholz *et al.*, 1969, p. 2058). Afterslip may in fact be essentially an aseismic phenomenon; although directly related to processes initiated during large earthquakes, the character of afterslip is thus far indistinguishable from that of fault creep.

Observations conducted by several different groups of investigators within a few days following the February 9, 1971, main shock quickly established that afterslip would make a relatively minor contribution to the total fault slip (Nason, 1971; Lahr *et al.*, 1971; Burford *et al.*, 1971). Precise leveling measurements across the Sylmar segment of the surface break repeated several times through a 200-day period by Sylvester and Pollard (this Bulletin) demonstrate that significant vertical displacements occurred, the character of which indicates definite, though minor, afterslip activity. Reports from local residents that offsets on minor fractures north of the Sylmar segment continued to grow for several days following the main shock indicate that afterslip may have been occurring on subsidiary faults (U.S. Geological Survey staff, 1971, p. 61).

Various measurement techniques were employed in the effort to detect afterslip at a number of localities along the prominent surface breaks. The methods included repeated distance ranging over certain of the long lines used in the horizontal displacement measurements described above, repeated measurements of horizontal angles and lengths within small-scale monument arrays, installation of a mechanical displacement recorder, and repeated leveling along lines of monuments traversing the tectonic surface ruptures. The repeated leveling was the most successful technique employed, both because the afterslip had a significant vertical component and because the afterslip activity was usually diffused across a fairly wide zone.

We earlier reported (Burford *et al.*, 1971, p. 84) changes in length for several lines (SF8 to PL1, PL1 to MAYS2, PE2 to SF8, and PL1 to PE2) in the post-earthquake period February 11 to February 23, 1971. These changes are now suspect as an intermittent malfunction in the temperature control of the crystal oven in the Geodolite was detected shortly after those preliminary surveys were completed. Thus, we cannot eliminate the possibility that the changes reported were merely a consequence of equipment failure. The surveys reported earlier in this paper were made after the malfunction was corrected.

Five small-scale monument arrays were installed across surface breaks during the week following the main shock, two on the Sylmar segment, one on the Tujunga segment, and two on separate breaks in the band of discontinuous fractures north of the Tujunga segment. The locations of these arrays are shown by positions of letter symbols A through E in figure 9. With one exception (site B) all of the array configurations were measured more than once during February, 1971, by occupying a central-point station with a Wild T-3 theodolite and measuring horizontal and vertical angles to the outlying monuments at distances between 50 and 225 m from the instrument station. Distances to two points from the instrument station within each array were measured by angle readings on Wild subtense bars. Repeated horizontal angle measurements were sufficiently precise for detection of horizontal displacements of about 1.5 to 5.5 mm (3 standard deviations), a range of resolution largely dependent upon distance from the instrument to the outlying station. On the same basis repeated vertical angle readings showed a range of resolution from about 1 to about 7.5 mm, while subtense-bar angle readings were only good for resolving horizontal distance changes greater than 15 mm.

Significant changes in the small-scale arrays were recorded at only two sites indicated in figure 9 as locations D and E. At the Pierce array (site D), measurements on February 24 compared with initial measurements on February 11, 1971, showed that a monument 85 m north of the most prominent fault scarp rose 3.2 ± 0.6 mm while a monument 85 m south of the scarp rose 1.9 ± 0.6 mm (standard deviations) relative to the instrument station. Measurements at the Tujunga array (site E) on February 23 compared with initial measurements on February 12, 1971, showed that a monument on the north side of minor surface cracks rose 9.7 ± 0.5 mm while a monument about 90 m south of the cracks dropped 3.7 ± 0.3 mm relative to the instrument station which was also south of the cracks by about 28 m. No other significant changes were detected in the remeasurements of the small-scale arrays.

A pair of vertical wire extensometers were installed in a borehole drilled through the bedding-plane reverse fault exposed in Lopez Canyon about 900 m north of the main break of the Tujunga segment (near site C, figure 9). The fault scarp site, instrument characteristics, and preliminary results were discussed in a previous report (Burford *et al.*, 1971, p. 84, 85). Unfortunately, considerable doubt was cast on the results from the extensometers due to discovery of possible instability in the instrument mounting frame at the time the site was abandoned in July, 1971. The casing for the borehole was supported in part by friction between the outer wall of the casing and the sidewall of the boring and in part by steel anchor-bars welded

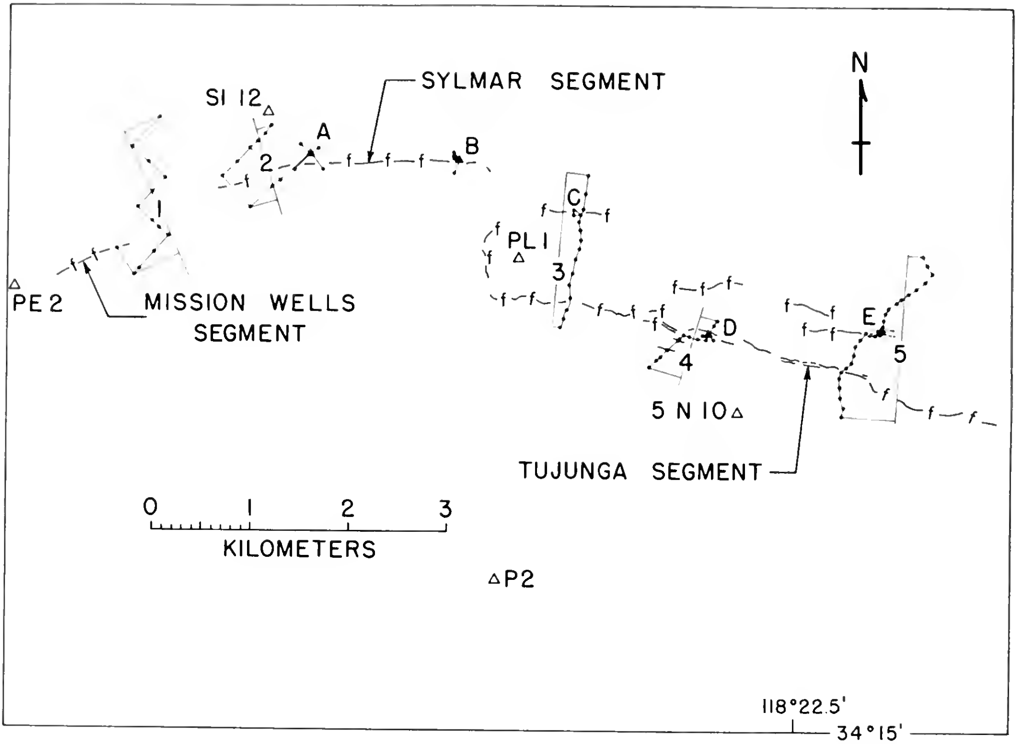


Figure 9. Index map of area surrounding the surface breaks showing the positions of monument arrays (A through E) and lines of repeated leveling (1 through 5) established for detection of displacements associated with afterslip.

to the outside of the casing and resting on the ground surface. The instruments were attached to a frame resting on the steel anchor-bars. During the time of operation, part of the casing load supported by friction was transferred to the anchor bars, perhaps particularly at the times of slight shaking during the larger aftershocks on February 20 (Burford *et al.*, 1971, table 3), when step-like vertical contraction events were recorded. Some vertical extension events were also recorded, however, and these were generally characterized by the gradual onset of displacement typical of creep events on the San Andreas fault. An interpretation of the vertical extension events recorded by the instruments as an indication of continued reverse slip on the fault plane is supported by slight changes in level readings across the scarp discussed below.

Repeated precise leveling observations were carried out by crews from the Topographic Division of the U.S. Geological Survey along several lines of monuments indicated in figure 9. The results of comparisons of each repeat traverse with the initial levels determined soon after the earthquake are shown in figure 10. Results from all but the Gridley line (Line 2 in figure 9) gave some indication of afterslip.

The Mission Wells line (line 1 in figure 9) was routed through a gap between the southwest end of the Sylmar segment and the northeast end of the Mission Wells segment of the surface break. However, the line was terminated on a bench mark along the railroad at a point near the northeast end of the Mission Wells segment. Fractures passed by both sides of the bench mark, and level changes at that point were somewhat erratic. Relative level changes at the remainder of the stations show that between February 21 and 22, 1971, the area along a projection of the ends of the two surface breaks was uplifted about 38 mm relative to the north end of the level line, and a tilt component of about 40 microradians in the direction N.26°W. was produced on the surface of the northwest block. The initial tilt and relative uplift subsequently collapsed and at the same time points southeast of the line connecting the ends of the two surface breaks began to drop, suggesting the growth of a downwarp or slight scarp facing southeast which had an additional height of about 17 mm by April 5, 1971, the time of the final observations.

Level changes detected along Lopez Canyon line (line 3 in figure 9) were relatively minor but some-

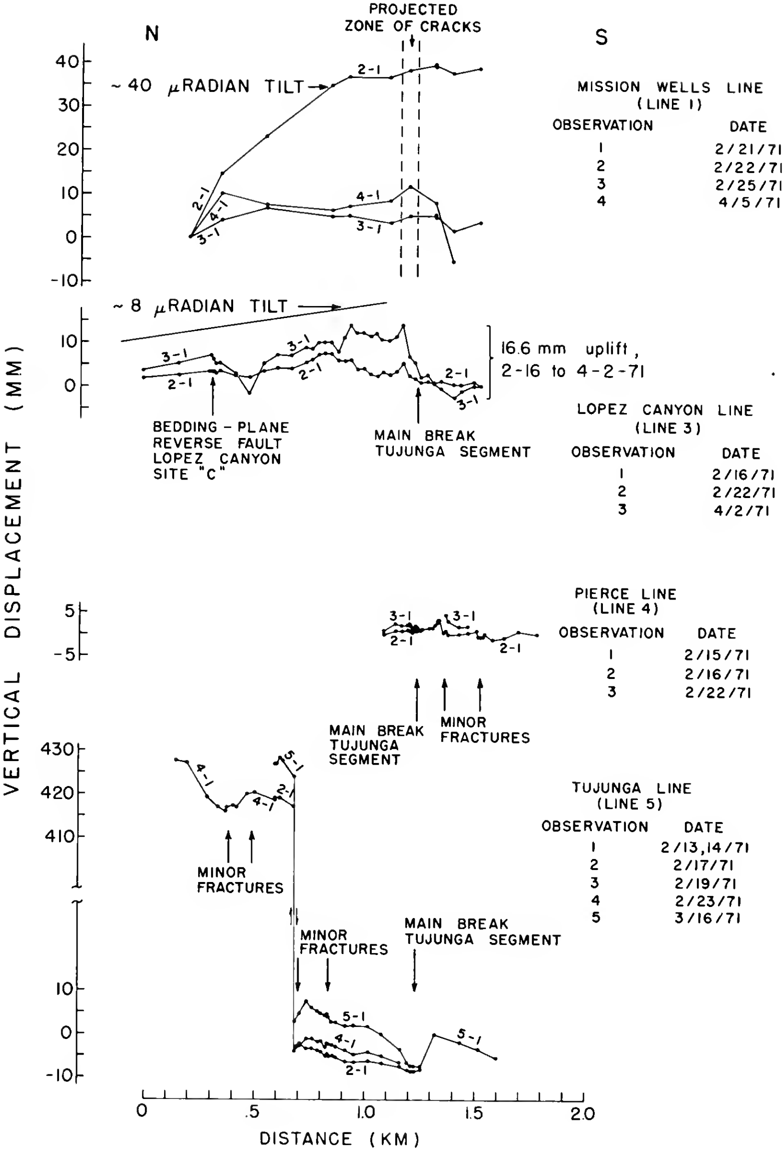


Figure 10. Profiles of vertical displacement along lines of repeated leveling following the main shock. Locations for the lines are given in figure 9. The displacement scale for the Tujunga line is broken in order to show displacement detail on either side of the interval showing a 0.42 m elevation change.

what similar to those along the Mission Wells line. During the period February 16 to April 2, 1971, the vertical component of displacement across the main break of the Tujunga segment increased by about 17 mm while an additional uplift of about 5 mm occurred across a 200 m zone including the surface trace of the reverse fault discussed above. The northward tilt of the surface north of the main fault break was increased by about 8 microradians during the period of repeated measurements.

Level changes along the Pierce line (line 4 in figure 9) are marginally significant but are consistent in indicating continued upwarping or slight growth of south-facing scarps across a 200 m zone on the south side of the most prominent surface break produced during the initial rupture. The maximum increase in the uplift from south to north was about 5 mm from February 15 to February 25, 1971. Afterslip at this locality was thus barely detectable and must have been restricted to extremely shallow portions of subsidiary slip planes, since the main scarp showed no significant continued displacement and the uplift died out a short distance north of the zone of afterslip activity.

The Little Tujunga line (line 5 in figure 9) showed minor changes in levels except for one interval in the vicinity of the east end of a discontinuous break passing through the center of Section 5, T. 2 N., R. 14 W. This interval showed a $+0.420$ m change between surveys on February 14 and 17, 1971. Other significant level changes occurred at the north end of the line, which developed an additional 15 to 20 mm upwarp, and at the site of the main break at the mouth of Little Tujunga Canyon, where stations 5 through 14 dropped 7 to 8 mm relative to adjacent points and a possible north-facing scarp 7.5 mm high might have developed just south of the main scarp.

The large uplift occurred within a zone of several minor fractures which showed only slight signs of afterslip activity. In spite of lack of evidence of major fracturing in the surface material, we conclude that the data are not in error and that the movement must have occurred. The change in level must represent the development of a south-facing monocline in surface materials caused by underlying eastward migration of slip off the end of the prominent ~ 0.5 m scarp well exposed in the adjacent stream bed (U.S. Geological Survey staff, 1971, figure 2).

Afterslip apparently was best developed across portions of the surface-break trend where the near-surface slip was either discontinuous or poorly developed. The measurements across the more prominent scarps such as along the main break of the Tujunga segment and the 0.8 m scarp north of the main break in Lopez Canyon showed only minor changes. Precise leveling was by far the most profitable technique employed in the search for evidence of afterslip, and should be considered the most effective potential method for afterslip studies following future earthquakes that are accompanied by surface faulting with appreciable dip-slip components.

ACKNOWLEDGMENTS

The installation and repeated measurements of the small-scaled monument arrays and the measurement of distances by Geodolite were carried out with the help of field crews of the Strain Studies Project, Office of Earthquake Research and Crustal Studies, U.S. Geological Survey. Stephen H. Kirby installed the vertical wire extensometers at the Lopez Canyon site. The bulk of postearthquake leveling data used to determine vertical deformation in the vicinity of the surface ruptures was provided by field crews and other personnel from the Field Surveys Section of the Topographic Division, U.S. Geological Survey. Data concerning changes in grade along the Wilson Drainage Channel and level changes at Lopez Dam were furnished by Frank Hubel of the Los Angeles Office of the District Engineer, U.S. Army Corps of Engineers. Data concerning changes in grade along Arroyo Avenue in the vicinity of the north-south zone of cracks connecting the west end of the Tujunga segment with the east end of the Sylmar segment were furnished by the City of Los Angeles through Rich C. Perman of the Survey Division, Van Nuys Office. Ivan Shinkle of the Los Angeles County Flood Control District provided additional leveling data and assisted in many other ways concerning the acquisition of geodetic data used in the study. An unpublished report summarizing the results from revision of geodetic control following the earthquake was provided by the Geodetic Section of the Survey Division, Department of County Engineer, County of Los Angeles. Arthur G. Sylvester and D. D. Pollard are thanked for furnishing their manuscript concerning afterslip on the Sylmar segment of the fault break prior to its publication in this Bulletin. We wish to thank John N. Alt and Robert O. Castle for providing unpublished leveling data allowing a preliminary comparison between local relative movement and vertical movement based on regional leveling. B. K. Meade furnished postearthquake geodetic distances for lines EAST to MISSION and EAST to MAY. The changes in elevations shown in figure 1 were compiled by the Geodetic Section, Survey Division, Department of County Engineer, Los Angeles County, from postearthquake levels run by Los Angeles City Bureau of Engineering, National Geodetic Survey, and Los Angeles County Engineer.

CHAPTER 15

Displacement on Tectonic Ruptures[1]

By Robert V. Sharp[2]

Tectonic slip was determined at 24 locations along surface ruptures formed at the time of the 1971 San Fernando earthquake. The slip vectors generally revealed a marked thrust component of movement, in addition to a left-lateral component, along the Tujunga segment of the San Fernando fault zone. However, slip vectors determined for the Sylmar and Mission Wells segments of the zone indicate much smaller thrust components and instead reflect movement consisting of predominant left-lateral and vertical components. The position and orientation of the rupture traces, when combined with dips inferred from the slip vectors, suggest substantial curvature of the principal fault surface at depth. The composite fault surface suggested by surficial dips and geologic structure is consistent with crustal uplift data and aftershock distribution.

Although tectonic ruptures formed by the 1971 San Fernando earthquake were clearly expressed at the ground surface, the fault surfaces generally were not exposed. As a consequence, the amount and direction of slip * on the faults were commonly not directly measurable. However, they could be measured indirectly by combining apparent offsets on natural and manmade features along the traces of the surface breaks. This paper describes and interprets a series of slip vectors at specific points along the fault traces (see figure 1); such information, in turn, reveals the dip of the fault at the surface of the earth (figure 2). The inferred dips, together with other dips measured at exposures of the faults, provide an important datum for reconstructing a composite slip surface in the shallow part of the crust. Surficial dips can then be compared to the probable orientation of the fault surface at greater depth, as derived from the relationship of the faults to bedding in the rocks, as well as the location of the main shock and the distribution of aftershocks. The array of slip vectors suggests important surficial deviations from the over-all slip model of simple left-oblique thrust faulting.

DETERMINATION OF SLIP VECTORS

In this study, slip vectors have been determined chiefly by geometrically combining a vertical component indicated by the height of a scarp with lateral separations or dimensional changes on two horizontal and nonparallel linear features offset by the fault. The geometric relation of the various measurements and the length and orientation of slip vectors is shown in figure 3. Because the slip vector and the strike of the fault at the point of observation both lie in the surface of fault movement, the orientation of the fault, including the direction and amount of dip, is established, as shown in figure 4.

Horizontal components of most slip vectors shown in figure 1 were determined either by field measurement of offset features or by scaling the offsets from 1:2400-scale vertical air photos. Horizontal offsets were measured in the field chiefly by projecting the position of an offset linear feature visually from the opposite side of the fault to the near side and scaling the offset with a tape; such determinations are probably accurate to within a tenth of a meter. In addition, horizontal dimensional changes that were more accurately measured by geodimeter along some streets in the San Fernando area are used in this study. Horizontal offsets scaled from air photos are about as accurate as those measured with a tape in the field; several checks of relatively large offsets determined from photos closely matched corresponding field measurements.

Vertical components of displacement were also determined by various methods. Most measurements were made by visual projection, using the ground surface on opposite sides of the fault scarp as the reference. A few measurements came from leveling surveys, and two were obtained from plane-table surveys of scarps on the trace of the fault (see notes in table 1). In general, control on the vertical components is probably about as accurate as that on the horizontal components.

To minimize errors in determining individual slip vectors, all the component offsets or dimensional changes were measured as near as possible to each other. This is important because a slip vector calculated from components measured at widely separated points is not necessarily a simple average of the actual slip at the two points. Relatively large errors could result if components were measured at various places along a fault strand where displacement was changing abruptly in either magnitude or direction, or both. Widely scattered measurements along the Tujunga segment probably could yield relatively large errors because slip appears to be moderately variable over short distances there. However, components were

* "Slip" refers herein to net movement (see figure 3).

[1] Publication authorized by the Director, U.S. Geological Survey.
[2] U.S. Geological Survey, Menlo Park, California.

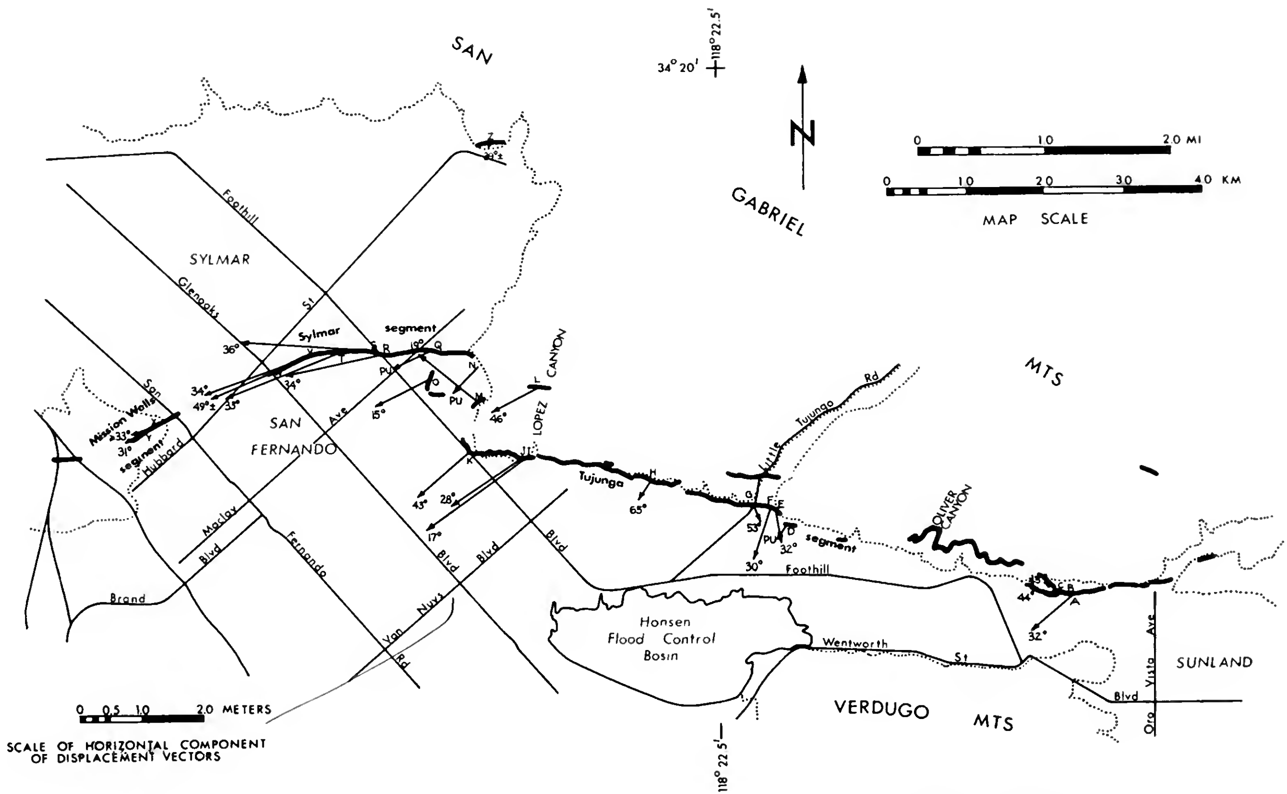


Figure 1. Movement of northern block with respect to the southern block, San Fernando earthquake of 1971. Length of arrows show horizontal component of calculated slip vectors (see table 1). Angle at head of arrow shows plunge of slip vector (plunge direction toward tail of arrow). PU means plunge unknown. Letters at tails of arrows identify vectors listed in table 1.

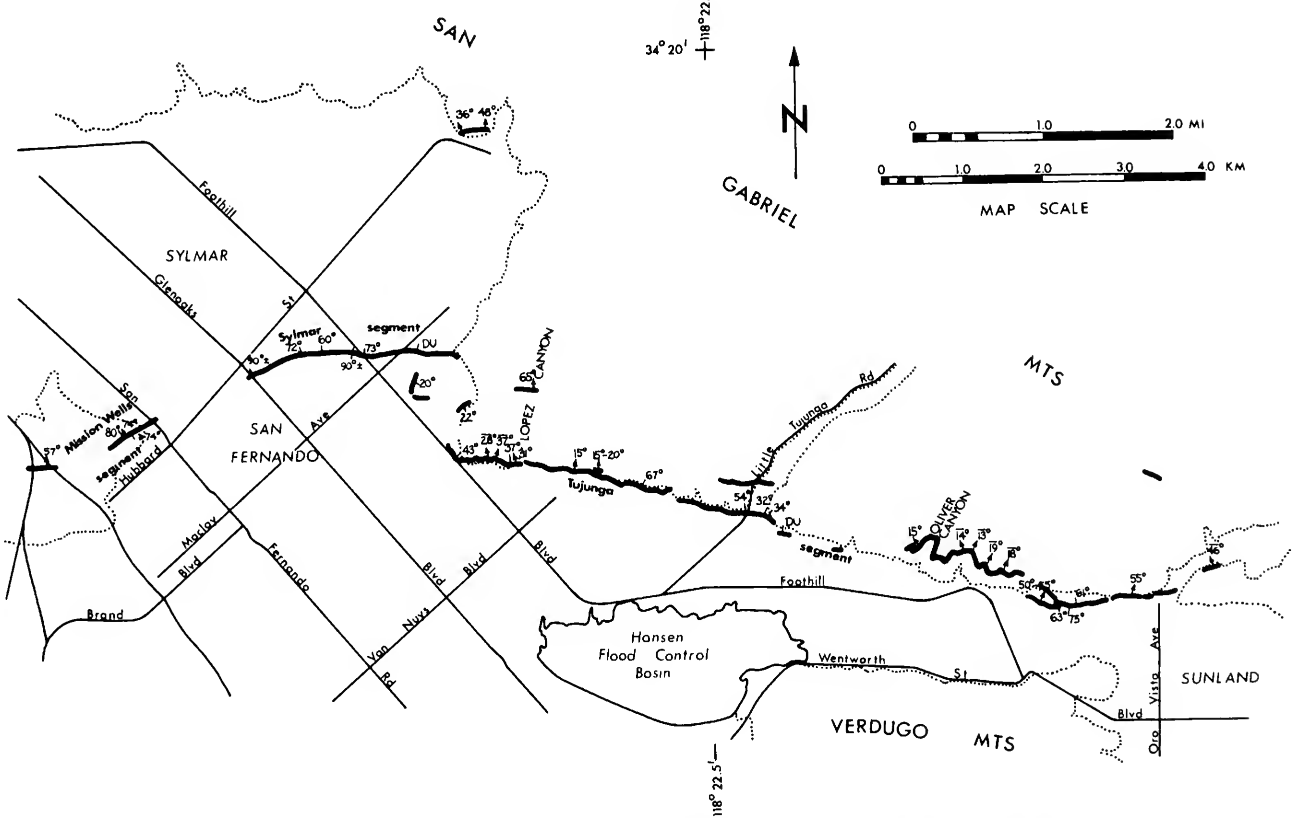


Figure 2. Dips of tectonic ruptures, San Fernando earthquake of 1971. Observed dips shown with arrow head on dip line. Bar over dip angle indicates average dip determined from trends of the fault trace over topography. Dips without arrow heads are calculated from slip vectors and fault strike. DU means dip unknown.

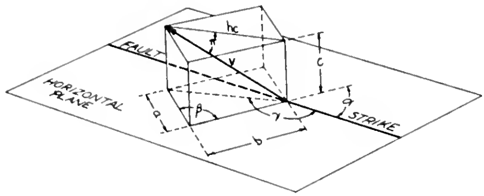


Figure 3. Three-dimensional view of a slip vector cell. Net slip vector V is cell diagonal. Apparent lateral separation a of linear feature at angle α from fault strike; apparent lateral separation b of second linear feature at angle β from first; vertical component of slip is c; plunge angle of slip vector is π; azimuth angle of slip vector (measured from fault strike) is γ; length of vectors shown in figure 1 corresponds to horizontal component of slip vector, hc.

measured within 25 m of each other along the Tujunga segment, so the computed slip vectors are probably reasonably accurate (see table 1). On the other hand, some parts of the rupture zone, for example the Sylmar segment (figure 1), show only slight changes in slip along much of the trace. When slip components from widely separated points along this fault segment are combined into a slip vector, the errors that result are probably only slight.

Three checks on the accuracy of the slip vectors are included among those shown on figure 1. Vector Y, on the Mission Wells segment, was determined at the location of an exposure of the fault surface that showed slickensides. The computed fault dip of 80° N is close to the observed dip of 74°; and the plunge of the computed slip vector, 31°N 59° E, closely corresponds to the observed slickenslides, which plunge 29° N 55° E. Vector I west of Lopez Canyon provided a more limited check in that the fault dip exposed in a trench dug after the earthquake was used to calculate the slip vector. However, the computed plunge of the slip vector, 17° N 55° E, corresponds closely to the plunge of slickenslides observed in the trench, 20° N 60° E. A third check, on vector L in upper Lopez Canyon, has been described previously by M. G. Bonilla (U.S. Geological Survey, 1971, p. 68–69); a moderate discrepancy between the computed slip vector and slickenslides exposed there suggests that the latter formed during a previous episode of fault movement.

DISPLACEMENT ON THE SAN FERNANDO FAULT ZONE

Tujunga Segment *

Slip varies more in amount and direction along the zone of surface ruptures from Pacoima Wash eastward to Sunland than along other segments of the 1971 breaks. The relatively large movement that was measured at the western end of the Tujunga segment (vectors I, J, K, figure 1 and table 1) is similar in amount and direction to that determined along the Sylmar segment just west of Pacoima Wash. The largest slip in the Tujunga segment (vector I), measured at the trailer park west of Lopez Canyon, was about 2.1 m. Its left-lateral component is about 2.4 times greater than the dip-slip component. Even larger slip (not indicated in figure 1) is suggested at a scarp 1.5 m high found farther east in Oliver Canyon (see Proctor and others, 1972, figures 10 and 12). A 20° dip on the fault there implies a slip vector of at least 4.4 m. However, Mr. R. Cowan, owner of the property, indicated that part of the present height of the scarp is pre-earthquake in age, so that slip there could not be accurately estimated. Although large slip is possible at Oliver Canyon, east of Lopez Canyon all measured slip vectors are smaller and generally less systematic than to the west. All but two vectors (B and C in Big Tujunga Wash) east of Lopez Canyon have a substantial compressional component normal to the fault trace. However, the sense of the lateral component changes from uniformly left-lateral in the western part to intermixed slightly right- or left-lateral vectors in the central part (vectors D through G) and back to uniformly left-lateral near the eastern terminus of ground rupture. Although nearly all of the vectors are consistent with southward overthrusting of the San Gabriel mountain mass relative to the valley, internal spreading and piling up in the overthrust block is also implied by the changes in sense of lateral components along the Tujunga segment. The two vectors that show predominantly strike-slip in Big Tujunga Wash (B and C) may reflect anomalous surface geometry of a northward-dipping thrust fault beneath the thick unconsolidated alluvium, despite the fact that the slip vectors indicate steep southward dip in the alluvial material. The sinuous traces of the faults there in fact suggest shallow-dipping slip surfaces.

Sylmar Segment

The trace of the Sylmar segment on the alluvial surface near the city of San Fernando is straighter and more continuous than along most of the Tujunga segment farther east. In terms of slip determined along this segment, it is the zone of both the most consistent and greatest measured fault displacements. Slip apparently is uniformly 2.0 m or greater from near the southwestern end of the segment at Glenoaks Boulevard eastward at least to Foothill Boulevard (vectors R through W, figure 1 and table 1). Moreover, the

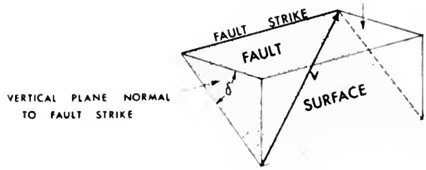


Figure 4. Relation of dip δ to slip vector V and fault strike. View from overhanging block.

* Includes "Tujunga" and "Lakeview" segments of Chapter 5 in this Bulletin. . . . Editor

Table 1. Fault slip vectors from features measured in the field.

VECTOR IN FIGURE 1	LOCATION	FEATURES MEASURED		MAXIMUM DISTANCE BETWEEN MEASURED FEATURES (m)	SLIP VECTOR[a]					DIP OF FAULT SURFACE	NOTES
		Vertical	Horizontal		Length (m)	Length of horizontal component (plotted in figure 1) (m)	Azimuth	Plunge	Sense of lateral component		
A	Big Tujunga Wash	Scarp	1 Offset dirt road 2. Offset linear mound	12	1.1	0.9	S 50°W	32°NE	Left	61°N	
B	Big Tujunga Wash	Scarp	1. Offset stream bank 2. Offset linear mound	25	0.8	0.6	N 80°W	44°E	Left	75°S	
C	Big Tujunga Wash	Scarp	1. No offset, dirt road 2. Offset linear furrow	12	0.4	0.3	N 60°W	45°SE	Left	63°S	
D	West end of Kurt Street	----	1. Compression in walk 2. No offset in walk	0	---	0.2	S 30°W	----	Left	----	
E	Orange grove east of Little Tujunga Wash	Scarp	1. Offset ranks of trees 2. Offset files of trees	3	0.6	0.5	S 1°E	32°N	Right	34°N	
F	Orange grove east of Little Tujunga Wash	Scarp	1. Offset ranks of trees 2. Offset files of trees	3	1.0	0.9	S 18°W	30°NE	Left	32°N	Average of 4 vectors from adjacent rows of trees.
G	Orange grove west of Little Tujunga Wash	Scarp	1. Offset ranks of trees 2. Offset files of trees	3	0.5	0.3	S 22°E	53°NW	Right	54°N	Average of 3 vectors from adjacent rows of trees.
H	0.7 km west of Bartholomaus Canyon	Multiple scarps	1. Compression in pipeline 2. Offset in pipeline	8	0.9	0.4	S 34°W	65°NE	Left	67°N	Vertical offset from plane table data by M. G. Bonilla (personal communication).
I	Trailer park west of Lopez Canyon	Scarp in drive	1. No offset, edge of drive 2. ----	4	2.1	2.0	S 55°W	17°NE	Left	31°N	Observed dip (in trench) used in calculating slip vector.
J	Trailer park west of Lopez Canyon	Scarp in drive	1. Offset block wall 2. Offset drive	5	1.4	1.2	S 56°W	28°NE	Left	37°N	
K	Convalescent hospital, Foothill Boulevard	Scarp in pavement	1. Offset driveway 2. Offset curb, Foothill Boulevard	30	1.5	1.1	S 46°W	43°NE	Left	43°NE	
L	Upper Lopez Canyon	Scarp	1. Offset of dirt mound 2. ----	12	1.3	0.9	S 63°W	46°NE	Left	65°N	From plane table data, U.S. Geological Survey Staff (1971).
M	End of Montero Avenue	Scarp in street	1. Offset of road 2. Compression in sidewalk	7	1.2	1.2	N 51°W	19°SE	Right	22°SE	From plane table data (M. G. Bonilla, personal communication).
N	0.6 km south of Lopez Dam	----	1. Compression in pipeline 2. Offset of pipeline	30	---	0.6	S 49°W	----	Right	----	No surficial break or vertical offset was evident.
O	Freeway 210 alignment near Pacoima Wash	Scarp	1. Offset fence, flood channel 2. Offset fence, freeway	125	1.0	1.0	S 63°W	15°NE	Right	20°E	
Q	MacNeill Street	----	1. Compression in pipeline 2. Offset curb	2	---	0.7	S 60°W	----	Left	----	No vertical components estimated because of vertical curvature of street.
R	Foothill Boulevard	Uplift in street	1. Offset pavement 2. Extension along pavement	0	2.0	1.6	S 78°W	34°E	Left	73°N	Extension between Fernmont Street and Maclay Avenue from survey data by City of Los Angeles.
S	Adelphia Avenue	Uplift of street	1. Offset on Adelphia Avenue 2. Offset on Harding Street	50	2.5	2.1	N 86°W	36°E	Left	~90°	Azimuth of slip vector essentially parallel to fault trace. Vertical offset from survey data by City of Los Angeles.
T	Eighth Street	Uplift of runoff conduit	1. Offset on Eighth Street 2. Offset on Fernmont Avenue	75	2.4	2.0	S 68°W	33°E	Left	60°N	Vertical offset from U.S. Army Corps of Engineers data.
V	Orange Grove Avenue	Uplift of street	1. Compression on Orange Grove 2. Offset on Orange Grove	0	2.5	2.0	S 69°W	34°E	Left	72°N	Compression from U.S.G.S. Geodimeter data.
W	Glenoaks Boulevard	Uplift of street	1. Offset on Glenoaks Boulevard 2. Extension on Glenoaks Boulevard	0	2.0	1.1	S 68°W	49°E	Left	~90°	Azimuth of slip vector essentially parallel to fault trace. Vertical offset from leveling data of Burford and others (1971). Extension from U.S. G.S. Geodimeter data.
X	Havana Avenue at Bleeker Street	Uplift of block wall	1. Offset sidewalk, Havana 2. Offset sidewalk, Bleeker	28	0.5	0.4	S 71°W	≥33°NE	Left	≥74°SE	Minimum plunge and dip from uncertainty in vertical component.
Y	Osceola Street near Bleeker Street	Uplift on sidewalk	1. Offset on sidewalk 2. Offset wall	20	0.5	0.4	S 59°W	31°NE	Left	80°NW	
Z	Tucker Avenue and Rajah Street	Uplift of street	1. No offset on curb, Rajah 2. ----	250	0.2	0.1	S 24°W	39°NE	Left	42°N	Average of observed dips used to caluculate slip vector.

[a] Movement of north side of fault relative to south.

horizontal component at Freeway 210 (0.2 km east of vector R) is also apparently greater than 2 m (a complete slip vector was not obtained there, however). The greatest slip occurred between Adelphia and Orange Grove Avenues (vectors S, T, and V), where it measured 2.4 to 2.5 m. The left-lateral component in this part was about 1.3 times as great as the dip-slip component. It is noteworthy that slip vectors in the Sylmar segment lie close to, or on line with, the trace of the principal break. Such a relation implies minor compressional components of offset normal to the fault trace, leaving transcurrent (strike slip) and vertical components as the dominant elements of movement.

Fault movement near the eastern end of the Sylmar segment and in the complex zone of surface rupturing and bending farther southeast in the San Fernando Industrial Park area appears to be substantially smaller than to the west. In spite of great variation in strike of individual ruptures, three of four slip vectors are oriented in the southwest quadrant essentially parallel to others farther west in the segment. One slip vector, N, was not associated with any obvious rupture, yet the ground changed dimensions by an amount consistent with other slip vectors in the general area. Vector M is unusual because it is oriented nearly perpendicular to all other slip vectors in the immediate area, but the anomaly could be explained by a large nontectonic component of thrusting at the toe of a large landslide mass on the steep slope immediately to the east. This interpretation is supported by abundant landslide scars observed on the slope and by geodetic data that show an anomalously large westward shift of the hilltop above the slope (Savage and others, this Bulletin, station PL 1 in figure 7).

Mission Wells Segment

Like the Sylmar segment, which is aligned with it, the Mission Wells segment is continuous and nearly straight. However, fault movement on this zone is much smaller than the largest found on the other segments. Two slip vectors, X and Y, are essentially equal, amounting to about 0.5 m of fault movement. The orientation of the slip vectors very nearly coincides with the trace of the fault rupture, as along much of the Sylmar segment. The left-lateral components apparently are about 1.5 to 1.7 times greater than the dip-slip components, a somewhat greater ratio than found along the Sylmar segment.

GEOMETRY OF THE FAULT SURFACES

Angles of dip of the tectonic ruptures that have been measured in the field or inferred from the slip vectors are shown in figure 2. These dips generally suggest that most of the fault segments that moved during the earthquake are essentially bedding-plane faults where they emerge at the ground surface. This general relationship is shown by exposures of the fault and bedding along the Tujunga segment, by bedding exposed near the Sylmar and Mission Wells segments, as well as by regional bedding orientation relative to the overall trace of surface rupture. The array of inferred and observed fault dips suggests that the Mission Wells and Sylmar segments on the valley surface dip steeply to vertically, whereas the Tujunga segment dips shallowly to moderately northward beneath the margin of the San Gabriel Mountains. The fault segments transecting the floor of San Fernando Valley are considerably straighter and more continuous than the breaks along the front of the range, which also suggests that the near-surface dip of the faults is steep. Despite the absence of obvious displacement at the northeastern end of the Mission Wells segment, right-stepping en echelon fractures observed on the natural ground surface also suggest left-lateral movement on a steep fault surface at that point.

By considering the relative positions of the fault traces and the fault dips and directions of slip, a fairly simple composite surface of tectonic movement was constructed that shows how the disconnected surface ruptures could merge into a single continuous zone of slip at depth. The shape of the slip surface, illustrated in figure 5, is designed to be consistent with geologic relationships at the surface and with the net regional dip indicated by aftershocks of the San Fernando earthquake.

The shape of the slip surface along the eastern part of the Sylmar segment and along the Tujunga segment has been drawn to reflect downward curvature of bedding in rocks adjoining the faults. Exposures of the fault in Cenozoic sediments along the Tujunga segment indicate that the slip surface is essentially parallel to bedding (Kamb and others, 1971; U.S. Geological Survey, 1971; Barrows and others, this Bulletin). The regional strike of bedding along the front of the San Gabriel Mountains also parallels the trace of the Tujunga segment (see Oakeshott, 1958, plate 1; Metropolitan Water District, 1968). Assuming that the observed conformable relationship holds for at least a short distance downdip, the slip surface would abruptly steepen only a few hundred meters north of its trace. This steepening is indicated by the general increase in dip of bedding from about 30° at the range front to as much as 85° a short distance farther north (Oakeshott, 1958; Metropolitan Water District, 1968). However, it should be emphasized that parallelism of the slip surface and bedding probably does not continue to a very great depth, perhaps less than 1 or 2 km, because aftershock data suggest a net regional northward dip on the fault surface of about 35° (Allen and others, this Bulletin), whereas regional geology suggests that bedding is steep to much greater depths. Thus, the inclination of the deep part of the Tujunga segment shown in figure 5 probably is similar to that observed at the fault trace.

A shallow-dipping range-front fault that rolls to a steeper dip while maintaining essentially the same strike may explain the pattern of maximum vertical uplift shown by Savage and others (this Bulletin, figure 2). Their data indicate that a linear maximum of crustal uplift immediately north of the Sylmar segment continues eastward into the projecting part of the San Gabriel Mountains, rather than deflecting southward around the margin of the range, as might be expected from the position of the trace of the Tujunga segment. The pattern of uplift could result from movement on a shallow-dipping fault that steepens as it approaches the ground surface.

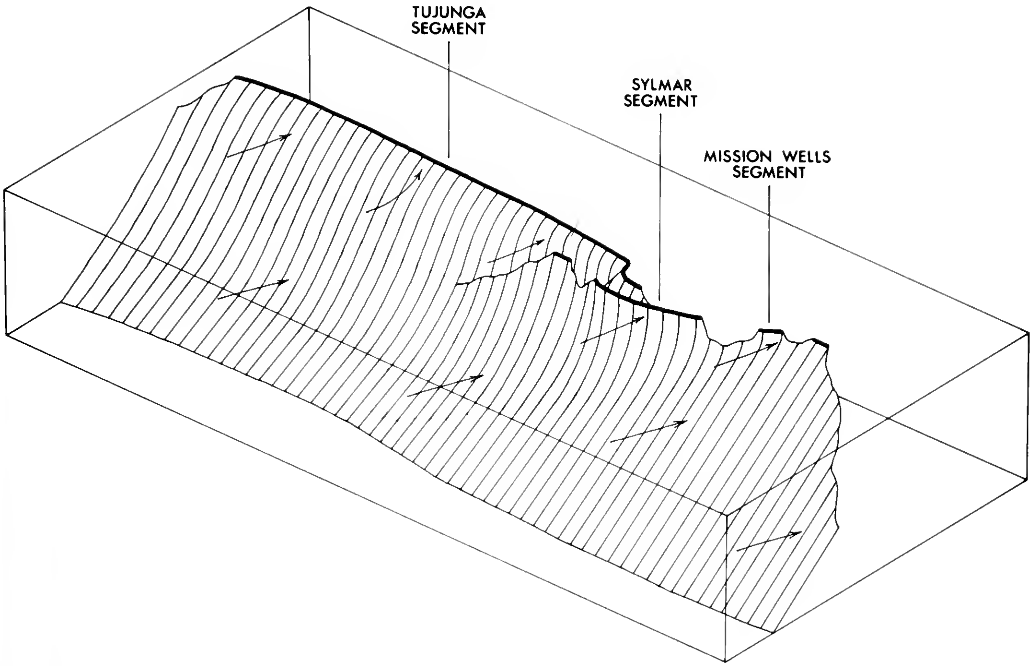


Figure 5. Generalized reconstruction of fault surface, San Fernando earthquake (view from northwest). Heavy lines show surface ruptures. Lines on fault surface drawn in direction normal to average trend of fault. Arrows on fault surface show approximate relative direction of slip of block north of fault.

Dips inferred from the slip vectors along the Sylmar segment are generally steep, but near its eastern terminus the fault apparently dips moderately to the north (see figure 2). The Sylmar segment may be nearly concordant in dip with the moderately steep bedding revealed at scattered exposures between Pacoima Wash and Hubbard Street (California State Water Rights Board, 1962, p. 52; Proctor and others, 1972, figure 3). In the same area, concordance in strike is shown by the attitude of bedding on both local and regional scales. For example, the apparent regional trend of the base of the Saugus Formation (see Oakeshott, 1958, plate 1), which is essentially conformable to bedding above and below the contact, is nearly parallel to the trace of the Sylmar and Mission Wells segments.

A similar parallelism between the slip surface and bedding is also suspected for the Mission Wells segment. Bedding is not known to be visible adjacent to the zone of surface rupture, but 0.4 km on strike from the west end of the 1971 break beds of the Pico Formation are essentially parallel to the steep fault surface exposed at vector Y (Oakeshott, 1958, plate 1).

If the probable steep surficial dip along the western part of the Sylmar segment and the Mission Wells segment is reconciled with the regional dip of the fault zone at greater depth, as shown by the locations of aftershock hypocenters (Allen and others, this Bulletin), another warp in the fault surface is suggested. In figure 5, this warp is depicted as the downward flattening of dip of these fault segments, joining an essentially smooth and shallow-dipping fault, the surface trace of which may lie at or near the Mission Hills thrust (see Oakeshott, 1958, plate 1). Southwestward motion of the northern block would not pile material up there, as along the eastern part of the 1971 surface ruptures if the dip is relatively smooth to the near surface. By contrast, along the zones where the dips are steep, the thrust component of movement at great depth may require upward release through a larger component of crustal uplift adjacent to the faults on the northern side.

The surficial dips inferred from the slip vectors and their downward projection suggested by surface geology provide the primary basis for the reconstruction of the warped fault surface shown in figure 5. The form of the fault surface at great depth is controlled only by the gross pattern of aftershocks. Although representation of the zone of rupturing at depth as a single surface is an oversimplification, in view of the irregular vertical distribution of aftershocks, much of the tectonic slip may have occurred within a relatively narrow zone of rock. Of course, considering that the ground surface broke at a number of places at considerable distance from the most prominent zone of rupture (see Barrows and others, this Bulletin), the pattern of fault slip in the overthrust montainous block is obviously more complicated than here suggested. However, the emergence of relatively steeply dipping ruptures, such as the scarp in upper Lopez Canyon near the concealed near-vertical zone of the fault surface, would be expected because the overthrust block must deform internally to accommodate the curvature of the principal slip surface.

The slip surface illustrated in figure 5 has an essentially smooth sole at great depth. According to Allen and others (this Bulletin, figure 5), however, the reason for the major southwestward deflection of the rupture trace in the western part of the Sylmar segment and in the Mission Wells segment is that the sole is warped at depth. Their inferred north-northeast-trending and steeply westward-dipping zone would raise the slip surface to a higher level east of the bend in the Sylmar segment. However, the probable bedding-plane slip relationship for most of the rupture zone suggests that the steeply dipping zones shown at or near the ground surface may effectively cancel the effect of the major irregularities of the fault traces. A reasonable downward projection of these steeply dipping zones could yield an approximately smooth sole for the principal slip surface, although the control on its shape at that depth admittedly is weak.

Surface and Subsurface Movements Determined by Remeasuring Gravity[1]

by H. W. Oliver,[2] S. L. Robbins,[2] R. B. Grannell,[3]
R. W. Alewine,[4] and Shawn Biehler[4]

ABSTRACT

Between March 1971 and February 1972, one to seven remeasurements of gravity were made at each of 88 gravity stations established between 1958 and 1970 in the vicinity of San Fernando by C. E. Corbato, R. B. Grannell, J. F. Long, W. F. Hanna, R. H. Chapman and S. L. Robbins. The gravity network was retied to the University of California at Los Angeles, where a tidal gravity record showed no gravity change at the time of the earthquake (L. B. Slichter, written communication, 1971).

Statistically significant decreases in gravity (>0.06 mgal) were recorded at about 20 stations north of the zone of thrust-fault surface ruptures. The maximum decrease measured was —0.45 mgal between Little Tujunga and Big Tujunga Canyons, where the interpolated elevation increase was about +2 m. In general, the gravity changes (Δg) are proportional to changes in elevation (ΔE) according to the least squares relation $\Delta g = -0.215 \Delta E \pm 0.026$ (s.d.), where ΔE in meters yields Δg in mgal. The slope, —0.215 mgal/m, corresponds to a Bouguer reduction density of 2.2g/cm^3). The changes in Bouguer anomalies reduced by the density of unsaturated alluvium (2.0 g/cm^3) are small ($\leq$0.08 mgal) and indicate that the uplift involved primarily the stacking of surficial-type layers on the pre-earthquake surface level, as might be expected in thrust faulting.

Detailed changes in Bouguer anomalies along Foothill Boulevard, though barely significant, are systematic, being generally positive north of the Sylmar segment of the surface ruptures. Corrections have been made for observed changes in the local water table level between 1958 and 1971; and the residual data were interpreted as a subsurface movement at a centroid depth of 120 m, perhaps representing the net sum of the displacements of the bottom 1–2 m of beds within the Cenozoic section by higher density beds beneath resulting from left-oblique reverse movement of the northern block.

The average free-air anomaly within the area of uplift increased about 0.20 mgal, whereas isostatic anomalies increased somewhat less, about 0.12 mgal; but that increase extended over a larger area. Whatever the state of isostatic compensation before the earthquake, the region of uplift is now slightly heavier. Much of the mass increase in the uplifted area may have come from the region of the epicenter, where a positive inverted "U" shaped gravity change can be explained by subsidence and mass removal.

On February 9, 1971, a moderate earthquake (approximately 6½ magnitude on the Richter scale) occurred in the northern San Fernando Valley and adjacent parts of the San Gabriel Mountains, California. The year following a study was made of gravity changes. Left oblique thrust-fault ruptures that formed along the San Fernando fault system strike approximately east-west and dip between 30° and 75° north (Sharp, this Bulletin; Barrows and others, 1971). Available data on change in elevation indicate that uplift associated with the faulting locally exceeded 2 m along an east-trending axis about 2 km north of the surface fractures; farther north, the amount of uplift decreased more gradually, exceeding +0.5 m for some distance into the San Gabriel Mountains (Burford and others, 1971; Savage and others, figure 2, this Bulletin). Precise data on leveling prior to the earthquake are not available for much of the San Gabriel Mountains, and the extent and amount of elevation change in the region 10–20 km north of the surface ruptures is not well known.

The core of the San Gabriel Mountains consists of Precambrian to Mesozoic metamorphic and plutonic rocks flanked by thick sections of Cenozoic marine and nonmarine sedimentary rocks. All of these rocks show widespread evidence of deformation throughout the Cenozoic Era (Oakeshott, 1958). The San Fernando Valley is a depositional basin with a thickness of as much as 5 km of sedimentary strata dating from middle Miocene time (Corbato, 1963). The northern margins of the Valley are bounded by a series of north-dipping thrust faults (Wentworth and Yerkes, 1971).

There have been limited studies of gravity changes accompanying previous earthquakes in Japan (Matuzawa, 1964, p. 41), in Alaska (Barnes, 1966, 1969; and

[1] Manuscript submitted for publication March 1972. Publication authorized by the Director, U.S. Geological Survey.

[2] U.S. Geological Survey, Menlo Park, California 94025.
[3] California State University, Long Beach, California 90840.
[4] Seismological Laboratory, California Institute of Technology, Pasadena, California 91109.
[5] Department of Geology, University of California, Riverside, California 92507.

Rice, 1969), and in New Zealand (Hunt, 1970). The most definitive of these studies is that by Barnes, who reported gravity changes at about 35 stations in Alaska after the 8.4-magnitude earthquake of March 27, 1964. The gravity changes (Δg) ranged from -0.4 to $+0.5$ mgal and, at least in the uplifted area, were related to elevation changes (ΔE) by the Bouguer relation for an assumed density of about 2.7 g/cm^3 ($\Delta g = -0.20\ \Delta E$, where ΔE in meters yields Δg in mgal). However, the Δg–ΔE data showed a significant scatter from linearity and suggested a free-air relationship (that is, $\Delta g = -0.31\ \Delta E$) over a portion of the downdropped area. Hunt (1970) also reported a Bouguer relation between gravity and elevation changes for the 1968 Inangahua (New Zealand) earthquake; but he had only two reoccupiable gravity stations within the uplifted area, and these showed a change in gravity of -0.18 and -0.36 mgal. The corresponding elevation changes were $+1.2$ and $+1.8$ m, giving slopes $\Delta g/\Delta E$ of -0.15 and -0.20 mgal/m, respectively.

These pioneer studies introduced a new method for studying geodetic movements associated with earthquakes, but their data were rather meager and the results inconclusive as regards both geodetic applications and the determination of subsurface movements.

As Barnes pointed out, the sensitivity, calibration, and stability of gravity meters are now sufficient to make studies reliable. There are two important requisites for detecting gravity changes: (1) the vertical component of tectonic displacements needs to be of the order of ⅓ m or more, as at San Fernando (horizontal displacements have not yet been studied and they will probably need to be large); and (2) reliable gravity stations must have been established in the area prior to the earthquake.

Finding reliable gravity stations to reoccupy after an earthquake is usually difficult. Fortunately, in the San Fernando area, the density of reoccupiable stations was such that a study could be made. These stations include: (a) a gravity survey of the San Fernando Valley by Corbato (1963) made in 1958 using a Worden gravimeter (W88) and very tight control; (b) unpublished data in the San Gabriel Mountains obtained by Shawn Biehler in 1964 and by R. B. Grannell and J. F. Long in 1970 using LaCoste and Romberg gravity meter G22; (c) two gravity base stations established by Chapman (1966) in 1963 using a LaCoste and Romberg gravimeter G22; (d) two mountain gravimeter calibration loops—(1) the Mt. Wilson loop established by Harrison and Corbato (1965) using a LaCoste and Romberg geodetic gravimeter (DL–1), located on the southeast side of the earthquake area, and (2) the Mt. Pinos loop established by the U.S. Geological Survey (Barnes and others, 1969) using several LaCoste and Romberg gravimeters, located northwest of the earthquake area; and (e) two U.S. Geological Survey field stations located about 13 km north of Newhall.

We regard all of the data of these surveys to be accurate to ±0.05 mgal or better, except those obtained by Grannell and Long, whose data in the San Gabriel Mountains have a marginal accuracy of ±(0.05–0.12) mgal. Because of their strategic location in areas where gravity changes of 0.10 to 0.50 mgal were considered possible on the basis of elevation changes, 40 of their stations were also reoccupied.

REOCCUPATION OF STATIONS

Between March 1971 and February 1972, one to seven remeasurements of gravity were made at each of 88 gravity stations selected from the surveys listed. Data for 48 of the 88 stations reoccupied are based on direct ties to either base station MW-1 located at the University of California at Los Angeles (UCLA) or base station MW-2 at the California Institute of Technology (Cal Tech) (figure 9). Grannell and Long's data were tied to Chapman's (1966) base station 307 at San Fernando City Hall. The base station at UCLA was Corbato's (1963) prime base for his San Fernando Valley survey and is the starting point of the Mt. Wilson calibration range. L. B. Slichter (written communication, 1971) provided a copy of UCLA's tidal gravimeter recording for the period covering several hours before until several hours after the earthquake (figure 1). Tidal gravity level before and after the shocks indicates that there was no gravity change at UCLA.

We are satisfied that there was no gravity change at Cal Tech within the reliability of five pre- and six post-earthquake measurements made with LaCoste and Romberg meters relative to UCLA or our prime base

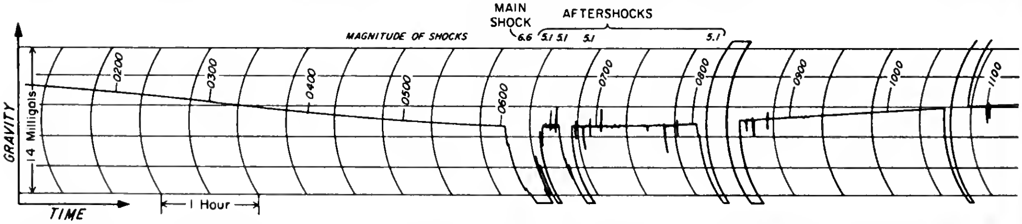


Figure 1. Tidal gravity meter record made at Earth Sciences building, University of California at Los Angeles on February 9, 1971. Hour marks from 0200 to 1100 shown on the record are in Pacific Standard Time. The magnitude of the main shock and the four aftershocks having magnitudes greater than 5 are shown at their approximate time positions after Allen and others (1971). Each of the 10 horizontal lines making up a vertical scale represent an increment of 0.014 mgal. Tidal gravity at UCLA had decreased about 0.3 mgal from 0200 to 0600:41.6 PST, the time of the main shock. The pen, after being knocked off scale, returned to the same sinuous level about 0620 PST after seismic motion from the second 5.1 magnitude aftershock had subsided. No earthquake-induced change in gravity occurred at UCLA greater than the accuracy of the record (±0.001 mgal).

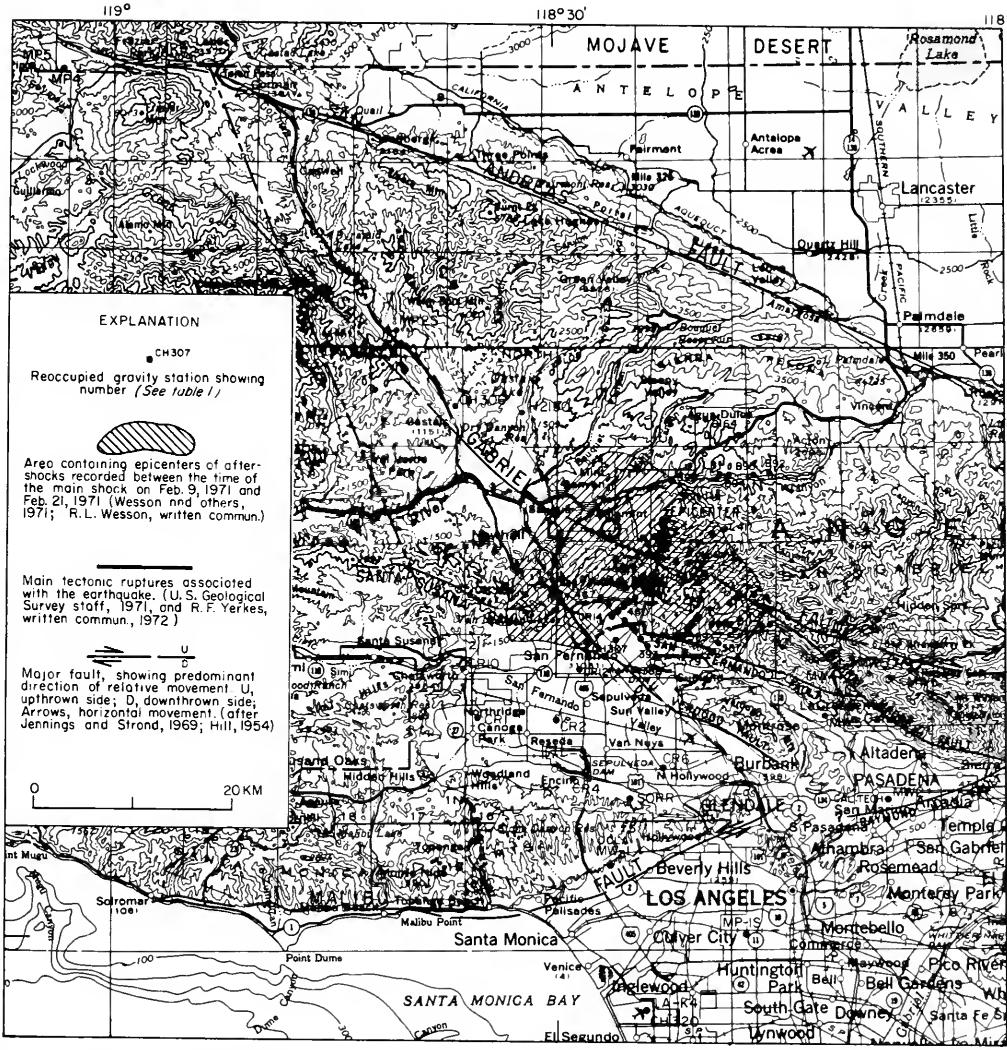


Figure 2. Index map of San Fernando and vicinity showing location of the earthquake epicenter, surface ruptures, inverted U-shaped area within which epicenters of aftershocks were distributed, and reoccupied gravity stations.

in Menlo Park (Oliver, 1965). The gravity difference (Δg) between the means of the two sets of data is $\Delta g = 0.00 \pm 0.05$ (s.d.) mgal.

Several ties have been made between the base station at UCLA and Chapman's base at San Fernando City Hall, a base station at Exposition Park, Los Angeles (MP-1S, one starting point for the Mt. Pinos calibration range), a U.S. Air Force base station (LA-K) at the Los Angeles International Airport (Jablonski, 1970), a California Division of Mines and Geology base station (CH320), also at the Los Angeles International Airport (Chapman, 1966), and the U.S. Geological Survey Regional Center in Menlo Park. None of these ties show evidence for any gravity change.

All of the above base station ties, the calibration loops to Mt. Wilson and Mt. Pinos, and most of Corbato's data in San Fernando Valley were remeasured with two LaCoste and Romberg gravity meters G17 and G161. These two meters were checked for calibration and stability just prior to and immediately after completion of the measurements by running them over the Mt. Hamilton calibration range east of San Jose, California (Barnes and others, 1969). The Biehler 1964 data and two of the Long pre-earthquake data in the San Gabriel Mountains were reoccupied by Biehler and S. W. Smith relative to the Cal Tech base with LaCoste and Romberg meter G22. The Grannell and the Long data were rerun using LaCoste and Romberg meter G141. The last group of reoccupation data, those along Foothill Boulevard in San Fernando (figure 6), were obtained primarily by Alewine using a Worden Master W533. Alewine made at least five ties to each of the eight stations, and his mean values were checked at two stations with LaCoste and Romberg instruments which agreed within ± 0.01 mgal. All of the reoccupation observed gravity values relative to UCLA or Cal Tech are probably accurate to ± 0.03 mgal, whereas the single loop data relative to San Fernando City Hall are considered reliable to ± 0.05 mgal (see Woollard, 1964).

Most of the 88 stations reoccupied are located within 5 km north of the tectonic ruptures, the area of greatest vertical movement (figure 2). Very little vertical control was available in the northeast part of the "area of aftershocks" reported by Wesson and others (1971) and reproduced in figure 2. We concentrated in this northeast sector and tried to bracket the area quickly to serve as a guide to the more accurate but much slower and expensive precision-level surveys for determining the extent of uplift.

Table 1 gives the principal facts for all the stations plotted in figure 2. The most important facts are the changes in gravity, elevation, and Bouguer anomalies. It is also important to note the years in which the pre-earthquake measurements were made, in particular the difference in the time the original gravity and the elevation controls were established; for example, 1964 versus 1929 respectively, for station B156. The uncertainties in both the gravity and elevation changes are somewhat variable and must be considered in interpretation of the data. The changes in Bouguer anomalies (table 1, last column) were calculated on the assumption that the surficial materials displaced above the pre-earthquake surface have a density of 2.0 g/cm^3. If the actual densities of these unsaturated late Cenozoic deposits were actually lower or higher by 0.2 g/cm^3, the changes in Bouguer anomalies would be altered by only 0.01 mgal per meter of elevation change.

The gravity changes within the immediate vicinity of the area of aftershocks (figure 2) are plotted and contoured as figure 3. The measured gravity changes marked by circled dots have been supplemented by releveling data converted to gravity changes according to the formula Δg (in mgal) $= -0.215\ \Delta E$ (in meters). This relation is based on a least squares linear fit of the data in table 1, for which both the gravity change (Δg) and elevation change (ΔE) were determined. These data are plotted on figure 4; the least squares line is shown and corresponds to a Bouguer gradient for a density (ρ) of 2.2 g/cm^3, a value slightly higher than the 2.0 g/cm^3 used in the reduction of Bouguer anomaly changes (table 1).

The measured gravity changes (figure 3) have been contoured with an interval of 0.1 mgal using the releveling data converted to equivalent-gravity-change as supplemental control. The general form of the contours is independent of the values computed from releveling data, the latter contributing mostly toward the closing of the -0.10 and -0.20 contours west of Sylmar and in the vicinity of Big Tujunga Canyon. In areas where the gravity and releveling data coincide or interfinger, they are surprisingly consistent within the uncertainties in the gravity changes of 0.04 to 0.10 mgal. This consistency and the continuity of plotted Bouguer anomalies within the contour pattern suggest that our calculated uncertainties (table 1) are somewhat conservative and that much of the gravity-change data is actually good to 0.01 to 0.04 mgal.

South of the zone of tectonic ruptures, measured gravity changes are less than the uncertainties of the measurements except at station CR12, located about 2 km south of San Fernando Dam (table 1, figure 2). The data for this station are enigmatic because they indicate a significant gravity decrease of 0.15 mgal at a location where it is rather certain that the elevation has not changed (see footnote 6, table 1). The gravity decrease is based on four independent ties yielding observed gravity values of -0.13, -0.13, -0.15, and -0.19 mgal lower than the average of Corbato's (1963) three measurements in 1958. The enigma could be an error in our relocation of Corbato's measurement; but the station is distinctive, being directly over a contractor's mark (Robbins and others, 1972). The apparent local decrease of about 0.15 mgal in Bouguer anomaly as well as in gravity may be real, and a closed -0.10 mgal contour around the station has been included in the contour map.

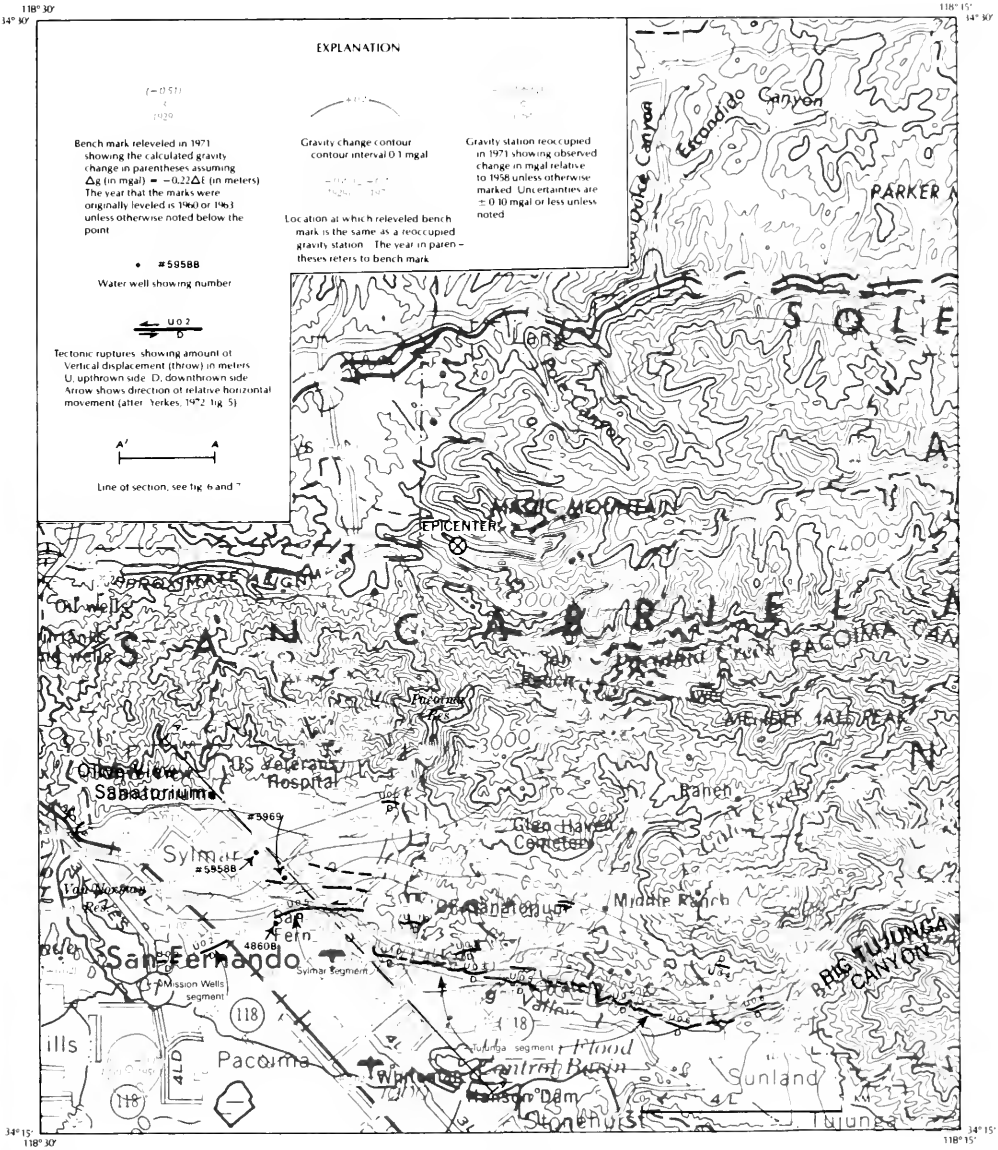


Figure 3. Contour map of gravity changes associated with the San Fernanda earthquake. Contours are cantrolled primarily by 30 pre- and post-earthquake measurements of gravity shown by circles. Changes in elevation at releveled bench marks shown by crosses have been converted to gravity changes according to the formula $\Delta g = -0.215\Delta E$ (see figure 4) and used to supplement the direct gravity measurements.

Table 1. Principal facts, including changes in gravity, elevation, and Bouguer gravity for 88 reoccupied stations plotted in figure 2. Changes in gravity in the immediate vicinity of the earthquake are plotted in figure 3.

Station No.	Previous elevation (meters)	Previous gravity −979,000 mgal[1]	Uncertainty[2] of measurement (σ_1)	Year	New gravity as of 1971 or 1972 −979,000 mgal	Uncertainty[2] of remeasurement (σ_2)	Gravity meters used and number of ties	Change in gravity Δg (mgal)	Uncertainty ($\sqrt{\sigma_1^2 + \sigma_2^2}$)[8]	Elevation change (ΔE) in meters[4]	Uncertainty in meters	Year of original measurement	Change in combined free-air and Bouguer correction (+ .2249ΔE)	Change in Bouguer anomalies (Δg + .2249ΔE) in mgal[5]	Source
PRIME BASES FOR REMEASUREMENTS															
MW-1[1]	133	597.60[1]	-	1965	597.60[1]	-	-	0.00[1]	-	?	-	-	-	?	Corbato
MW-2	232	578.88	±0.03	1965	578.88	±0.04	G17, G161 (6)	+0.00	±0.05	?	-	-	-	?	S. L. Robbins
STATIONS NORTH OF SURFACE RUPTURES															
CR14	373.1	526.02	±0.03	1958	525.72	±0.02	G17, G161 (4)	-0.30	±0.04	+1.35	±0.05	1960	+0.30	0.00	Corbato (1963)
CR444	352.2	530.38	±0.05	1958	530.28	±0.03	G17, WM533 (7)	-0.10	±0.06	+0.25	±0.12	1960	+0.06	-0.06	Corbato (1963)
CR446	363.8	527.52	±0.05	1958	527.40	±0.03	WM533, G17, G161 (8)	-0.32	±0.06	+0.16	±0.03	1960	+0.04	-0.08	Corbato (1963)
CR448	378.8	525.03	±0.05	1958	524.71	±0.03	WM533, G17, G161 (6)	-0.32	±0.06	+1.47	±0.03	1960	+0.33	+0.01	Corbato (1963)
CR449	363.9	527.62	±0.05	1958	527.57	±0.03	WM533, G17, G161 (6)	-0.05	±0.06	+0.32	±0.03	1960	+0.07	+0.02	Corbato (1963)
CR458	395.5	523.38	±0.05	1958	523.17	±0.03	WM533, G17, G161 (6)	-0.21	±0.06	+1.17	±0.06	1960	+0.26	+0.05	Corbato (1963)
CR459	420.6	519.73	±0.05	1958	519.54	±0.03	G17, G161 (2)	-0.19	±0.06	+0.98	±0.05	1960	+0.22	+0.03	Corbato (1963)
CR460	453.3	515.30	±0.05	1958	515.20	±0.03	G17, G161 (2)	-0.10	±0.06	+0.58	±0.03	1960	+0.13	+0.03	Corbato (1963)
CR461	504.1	507.17	±0.05	1958	507.08	±0.03	G17, G161 (2)	-0.09	±0.06	+0.48	±0.03	1960	+0.11	+0.02	Corbato (1963)
CR464	406.9	521.28	±0.05	1958	521.18	±0.03	WM533 (6)	-0.10	±0.06	+0.44	±0.03	1960	+0.10	0.00	Corbato (1963)
CR467	429.2	518.28	±0.05	1958	518.20	±0.04	WM533 (5)	-0.08	±0.06	+0.50	±0.03	1960	+0.11	+0.03	Corbato (1963)
CR559	374.0	536.37	±0.05	1958	536.01	±0.03	G17, G161, G141, G22 (5)	-0.37	±0.06	+1.49	±0.03	1960	+0.34	-0.02	Shawn Biehler
B92	697.7	504.66	±0.05	1964	504.61	±0.03	G22 (2)	-0.05	±0.06	?	-	-	-	?	Shawn Biehler
B93	674.2	508.96	±0.05	1964	508.90	±0.03	G22 (2)	-0.06	±0.06	?	-	-	-	?	Shawn Biehler
B94	627.6	517.93	±0.05	1964	517.97	±0.03	G22 (2)	+0.04	±0.06	?	-	-	-	?	Shawn Biehler
B95	528.8	537.18	±0.05	1964	537.08	±0.03	G22 (2)	-0.10	±0.06	?	-	-	-	?	Shawn Biehler
B155	1097.3	410.65	±0.05	1964	410.52	±0.03	G22 (2)	-0.13	±0.10	?	-	-	-	?	Shawn Biehler
B156	722.4	460.44	±0.05	1964	460.24	±0.03	G22 (2)	-0.20	±0.10	+0.67	±0.05	1929	+0.15	-0.05	Shawn Biehler
B164	755.3	494.15	±0.05	1964	494.13	±0.03	G22 (2)	-0.02	±0.06	?	-	-	-	?	Shawn Biehler
B581	455.7	557.46	±0.05	1964	557.01	±0.03	G22 (2)	-0.45	±0.15	?	-	-	-	?	Shawn Biehler
Base 1	?	?	±0.03	1970	?	±0.03	G22 (1)	-0.02	±0.10	?	-	-	-	?	J. L. Long (1971*)
L41	1406.6	351.80	±0.05	1970	351.83	±0.08	G141 (1)	+0.03	±0.10	?	-	-	-	?	J. L. Long (1971*)
L67	716	488.86	±0.08	1970	488.85	±0.06	G141 (1)	-0.01	±0.10	?	-	-	-	?	J. L. Long (1971*)
L74	750	475.72	±0.08	1970	475.61	±0.06	G141 (1)	-0.11	±0.10	?	-	-	-	?	J. L. Long (1971*)
L77	509.3	520.49	±0.05	1970	520.31	±0.03	G22, G141 (2)	-0.18	±0.08	+0.73	±0.05	1929	+0.16	-0.02	J. L. Long (1971*)
GR4	384	536.80	±0.06	1970	536.37	±0.05	G141 (1)	-0.43	±0.08	+1.91	±0.03	1929	+0.43	0.00	R. B. Grannell
GR5	400	533.78	±0.06	1970	533.39	±0.08	G141 (1)	-0.39	±0.10	?	-	-	-	?	R. B. Grannell

GR6	411	532.70	±0.06	1970	532.46	±0.07	G141 (1)	-0.24	±0.09	?	-	-	-	?	R. B. Grannell
GR7	437	528.87	±0.06	1970	528.63	±0.07	G141 (1)	-0.24	±0.09	?	-	-	-	?	R. B. Grannell
GR8	454	519.02	±0.08	1970	519.01	±0.05	G141 (1)	-0.01	±0.10	?	-	-	-	?	R. B. Grannell
GR9	558	519.46	±0.13	1970	519.34	±0.08	G141 (1)	-0.12	±0.15	?	-	-	-	?	R. B. Grannell
GR10	602	514.26	±0.13	1970	514.14	±0.08	G141 (1)	-0.12	±0.15	?	-	-	-	?	R. B. Grannell
GR11	1079	415.25	±0.10	1970	415.18	±0.06	G141 (1)	-0.07	±0.12	?	-	-	-	?	R. B. Grannell
GR12	1170	399.44	±0.10	1970	399.44	±0.06	G141 (1)	0.00	±0.12	?	-	-	-	?	R. B. Grannell
GR13	1122	412.81	±0.10	1970	412.84	±0.06	G141 (1)	+0.03	±0.12	?	-	-	-	?	R. B. Grannell
GR14	1255	387.40	±0.08	1970	387.53	±0.06	G141 (1)	+0.13	±0.10	?	-	-	-	?	R. B. Grannell
GR15	1407	352.87	±0.08	1970	352.97	±0.06	G141 (1)	+0.10	±0.10	?	-	-	-	?	R. B. Grannell
GR16	532	511.80	±0.08	1970	511.75	±0.06	G141 (1)	-0.05	±0.10	?	-	-	-	?	R. B. Grannell
GR17	520	510.90	±0.08	1970	510.94	±0.06	G141 (1)	+0.04	±0.10	?	-	-	-	?	R. B. Grannell
GR18	972	422.45	±0.08	1970	422.56	±0.08	G141 (1)	+0.11	±0.11	?	-	-	-	?	R. B. Grannell
GR19	1072	407.42	±0.08	1970	407.49	±0.06	G141 (1)	+0.07	±0.10	?	-	-	-	?	R. B. Grannell
GR20	1181	381.58	±0.08	1970	381.66	±0.06	G141 (1)	+0.08	±0.10	?	-	-	-	?	R. B. Grannell
GR21	1045	410.06	±0.08	1970	410.26	±0.06	G141 (1)	+0.20	±0.10	?	-	-	-	?	R. B. Grannell
GR22	749	474.79	±0.08	1970	474.77	±0.06	G141 (1)	-0.02	±0.10	?	-	-	-	?	R. B. Grannell
GR23	1186	375.15	±0.08	1970	375.17	±0.09	G141 (1)	+0.02	±0.12	?	-	-	-	?	R. B. Grannell
GR24	1068	396.63	±0.08	1970	396.71	±0.08	G141 (1)	+0.08	±0.11	?	-	-	-	?	R. B. Grannell
GR25	1022	409.23	±0.08	1970	409.18	±0.08	G141 (1)	-0.05	±0.11	?	-	-	-	?	R. B. Grannell
GR26	933	430.11	±0.08	1970	430.02	±0.08	G141 (1)	-0.09	±0.11	?	-	-	-	?	R. B. Grannell
GR27	842	445.87	±0.08	1970	445.74	±0.09	G141 (1)	-0.13	±0.12	?	-	-	-	?	R. B. Grannell
GR28	927	437.40	±0.08	1970	437.30	±0.06	G141 (1)	-0.10	±0.10	?	-	-	-	?	R. B. Grannell
GR29	1093	394.35	±0.08	1970	394.34	±0.06	G141 (1)	-0.01	±0.10	?	-	-	-	?	R. B. Grannell
GR30	722	471.71	±0.08	1970	471.79	±0.06	G141 (1)	+0.08	±0.10	?	-	-	-	?	R. B. Grannell
GR31	809	450.72	±0.08	1970	450.74	±0.06	G141 (1)	+0.02	±0.10	?	-	-	-	?	R. B. Grannell
GR32	910	431.23	±0.08	1970	431.38	±0.09	G141 (1)	+0.15	±0.12	?	-	-	-	?	R. B. Grannell
GR33	1169	378.95	±0.08	1970	379.08	±0.09	G141 (1)	+0.13	±0.12	?	-	-	-	?	R. B. Grannell
GR34	1203	369.53	±0.08	1970	369.67	±0.06	G141 (1)	+0.14	±0.10	?	-	-	-	?	R. B. Grannell
GR35	1250	367.31	±0.08	1970	367.36	±0.06	0141 (1)	+0.05	±0.10	?	-	-	-	?	R. B. Grannell
GR36	1108	385.68	±0.08	1970	385.99	±0.06	G141 (1)	+0.31	±0.10	?	-	-	-	?	R. B. Grannell
STATIONS SOUTH OF SURFACE RUPTURES															
CR1	240.7	567.35	±0.03	1958	567.39	±0.03	G17, G161 (2)	+0.04	±0.04	?	-	-	-	?	Corbato (1958)
CR2	235.9	563.19	±0.03	1958	563.20	±0.02	G17, G161 (4)	+0.01	±0.04	-0.03	0.03	1970	-0.01	0.00	Corbato (1958)
CR4	222.4	589.34	±0.03	1958	589.34	±0.08	WM533, G17, G161 (4)	0.00	±0.09	?	-	-	-	?	Corbato (1958)
CR6	193.3	579.19	±0.03	1958	579.16	±0.03	G17, G161 (2)	-0.03	±0.04	?	-	-	-	?	Corbato (1958)
CR10	293.8	571.25	±0.03	1958	571.25	±0.03	G17, G161 (2)	0.00	±0.04	?	-	-	-	?	Corbato (1958)
CR12	284.2	539.70	±0.03	1958	539.55	±0.03	G17, G161, WM533 (4)	-0.15	±0.04	0.00	±0.03	1963	0.00	-0.15	Corbato (1958)
CR388	301.9	543.97	±0.05	1958	543.99	±0.03	G17, G161 (2)	+0.02	±0.06	-0.05	±0.03	1960	-0.01	+0.01	Corbato (1958)
CR393	352.8	534.83	±0.05	1958	534.78	±0.03	WM533 (5)	-0.05	±0.06	+0.01	±0.03	1960	0.00	-0.05	Corbato (1958)
CR579	345.3	550.27	±0.05	1958	550.29	±0.03	G17, G161 (2)	+0.02	±0.06	-0.02	±0.03	1960	0.00	+0.02	Corbato (1958)
LA-K	38.0	597.03	±0.05	1966	597.03	±0.04	G17, 116 (6)	0.00[1]	±0.07	?	-	-	-	?	C. T. Whalen (1968*)
CH307	328.9	530.01	±0.05	1963	530.01	±0.01	G17, 116 (4)	0.00	±0.05	-0.06	±0.04	1960	-0.01	-0.01	Chapman (1966)
SORR	275	571.20	±0.05	1965	571.16	±0.04	G17, G161 (16)	-0.04	±0.06	?	-	-	-	?	S. L. Robbins
GR1	329	551.54	±0.06	1970	551.52	±0.05	G141 (1)	-0.02	±0.08	?	-	-	-	?	R. B. Grannell
GR2	349	545.99	±0.06	1970	546.00	±0.05	G141 (1)	+0.01	±0.08	?	-	-	-	?	R. B. Grannell
STATIONS NEAR CASTAIC															
CH306	374.9	543.27	±0.05	1963	543.19	±0.03	G17, 161 (4)	-0.08	±0.06	?	-	-	-	?	Chapman (1966)
H2150	401.4	538.86	±0.05	1968	538.81	±0.04	G17, 161 (2)	-0.05	±0.07	?	-	-	-	?	W. F. Hanna (1971*)

Station No.	Previous elevation (meters)	Uncertainty[2] of measurement (σ_1)	Previous gravity −979,000 mgal[1]	Year	New gravity as of 1971 or 1972 −979,000 mgal	Uncertainty[3] of remeasurement (σ_2)	Gravity meters used and number of ties	Change in gravity Δg (mgal)	Uncertainty $(\sqrt{\sigma_1{}^2 + \sigma_2{}^2})^8$	Elevation change (ΔE) in meters[4]	Uncertainty in meters	Year of original measurement	Change in combined free-air and Bouguer correction (+.2249ΔE)	Change in Bouguer anomalies (Δg + .2249ΔE) in mgal[5]	Source
MT. PINOS LOOP															
MP-1S	55	578.31	±0.02	1970	578.32	±0.03	G17, 161 (8)	+0.01	±0.04	?	-	-	-	?	W. F. Hanna (1969*)
MP-2S	789	472.12	±0.02	1970	472.07	±0.05	G17, 161 (4)	-0.05	±0.05	?	-	-	-	?	W. F. Hanna (1969*)
MP-3S	1540	361.00	±0.02	1970	361.00	±0.02	G17, 161 (4)	0.00	±0.03	?	-	-	-	?	W. F. Hanna (1969*)
MP-4S	2060	258.53	±0.02	1970	258.54	±0.01	G17, 161 (7)	+0.01	±0.02	?	-	-	-	?	W. F. Hanna (1969*)
MP-5S	2530	153.23	±0.02	1970	153.24	±0.04	G17, 161 (7)	+0.01	±0.04	?	-	-	-	?	W. F. Hanna (1969*)
MT. WILSON LOOP															
MW-1	133	597.60	-	1965	597.60	-	-	0.00	-	?	-	-	-	?	Corbato
MW-2	232	578.88	±0.03	1965	578.88	±0.04	G17, G161 (6)	+0.00	±0.05	?	-	-	-	?	S. L. Robbins
MW-3	510	522.48	±0.04	1965	522.49	±0.02	G17, G161 (6)	+0.01	±0.07	?	-	-	-	?	S. L. Robbins
MW-4	680	480.28	±0.06	1965	480.28	±0.02	G17, G161 (6)	0.00	±0.06	?	-	-	-	?	S. L. Robbins
MW-5	1108	398.57	±0.04	1965	398.52	±0.01	G17, G161 (4)	-0.05	±0.04	?	-	-	-	?	S. L. Robbins
MW-6	1410	334.61	±0.05	1965	334.56	±0.03	G17, G161 (4)	-0.05	±0.06	?	-	-	-	?	S. L. Robbins
MW-7	1718	255.15	±0.04	1965	255.10	±0.06	G17, G161 (4)	-0.05	±0.07	?	-	-	-	?	S. L. Robbins

*Written communication

[1] All observed gravity values listed in this table are relative to the gravity value at UCLA (Air Force execenter LA-B) of *979597.60* mgal and are on the Woollard and Rose (1963) datum. *Six* ties were made in 1971 to the prime Air Force base at Los Angeles Airport (LA-K); these data indicate that *0.74* mgal should be subtracted from all values in this table to convert the data to the new U.S. National Base Net datum (Schwimmer and Rice, 1969; Jablonski, 1970).

[2] The uncertainties of Corbato's base stations (±0.05) are based on the repeatability of his measurements (Corbato, 1963, p. 10), and can be viewed as standard deviations. All remaining uncertainties are standard deviations.

[3] These uncertainties are based on the standard deviations of the scatter in data about the mean values reported and are generally conservative.

[4] Elevation changes at bench marks along Foothill Boulevard were made available by the Bureau of Engineering, City of Los Angeles. Other changes are after Burford and others (1971) and J. P. Church (written communication, 1971).

[5] These changes in Bouguer gravity have the same uncertainties as the change in gravities listed in a preceding column (mostly ± 0.06 mgal) except for station 444. Because of the latter's large elevation uncertainty of ±0.12 m, the uncertainty in Bouguer anomaly change is $\pm\sqrt{[.06^2 + (.2249 \times .12)^2]} = \pm.07$ mgal.

[6] This station has been releveled twice since 1958 and found to have gone up 0.06 m between 1963 and 1970 and down 0.06 m between 1970 and post-quake measurements in 1971.

[7] The measurements on the Mt. Wilson Loop in 1965 and 1971 were made with the same LaCoste and Romberg gravity meter (G17), whereas the earlier measurement by Harrison and Corbato (1965) made in 1958 were obtained using LaCoste and Romberg DL-1. The differences in gravity between 1958 and 1965 are somewhat larger than those listed in the table for 1965 and 1971 but include the added uncertainty of comparing results with different meters over rather large gravity differences where calibration becomes a problem. The 1965–58 gravity differences relative to UCLA based on G17- DL-1 measurements at MW2, . . . MW7 are +0.05, +0.19, +0.11, +0.18, +0.11, +0.14, mgal, respectively.

[8] Stations with this footnote number have an added uncertainty in gravity change due to possible relocation error.

[9] No absolute gravity value is available for this station because it was on a local floating datum and not tied to Cal Tech prior to the earthquake. However, the station was retied relative to its local datum and the measured difference is meaningful.

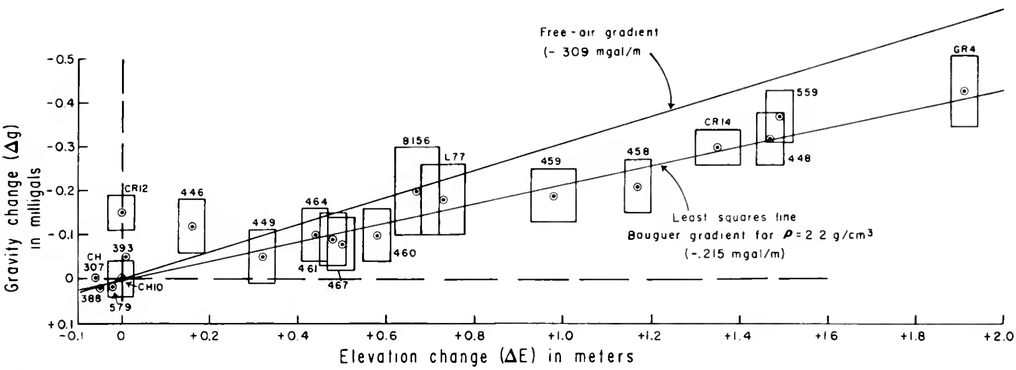


Figure 4. Plot of gravity changes versus elevation changes listed in table 1. Corresponding station numbers and rectangles of uncertainty are indicated for each point. A least squares line was fit to all points having a $\Delta E > 0.2$ m except B156 and L77; these points were deleted from the calculation because of their larger uncertainty (±0.10 mgal). Least squares line corresponds to a simple Bouguer relation between Δg and ΔE, assuming the average density of rocks making up the elevation change is 2.2 g/cm³. A line corresponding to the free-air gradient is shown for comparison.

EVIDENCE FOR SURFACE MOVEMENTS

A plot of gravity changes with changes in elevation (figure 4) shows a nearly linear relation. This means that the gravity remeasurements, where available, can be used to predict rapidly and help guide the slower and more costly releveling measurements. From figure 4, we have the least squares relation

$$\Delta g = -0.215\ \Delta E \pm 0.026\ \text{(s.d.)} \qquad (1)$$

where the elevation change ΔE in meters yields a gravity change Δg in mgal. In the calculation, stations 393, 446, B156, and L77 were not included, either because their elevation changes were small (<0.2m) and would unduly bias the computed slope or because uncertainty in the gravity changes (±0.10 mgal) is relatively large. The least squares line was also computed including these four stations—making a total of 14 Δg —ΔE points—and their effect is to increase the slope (absolutely) to —0.224 mgal/m and to increase the standard deviation to 0.040 mgal. The objective inclusion of all data yields a least squares slope that is still significantly less than the free-air gradient (—0.309 mgal/m) and correspond to a Bouguer reduction density of 2.0 g/cm³.

Preferring equation (1) above, the reciprocal relation for geodetic purposes becomes, to two significant figures:

$$\Delta E = -4.5\ (\Delta g \pm \sigma) \qquad (2)$$

where σ is the uncertainty in the gravity change. For example, for station CR14 (table 1), $\Delta g = 0.30$ mgal and $\sigma = \pm 0.04$, making the predicted ΔE from the measured gravity change 4.5 $(0.30 \pm 0.04) = 1.35$ m $\pm$ 0.18 m. Other examples, such as station 446, would not agree as well with the measured elevation change.

A comparison of the gravity change contours (figure 3) with the contour map of elevation changes (Savage and others, this Bulletin, figure 2) further attests to the close relation between the two sets of data. (The 0.10 mgal contour interval on the gravity change map is nearly equivalent to the 0.5 m interval on the elevation change map.) The northward bulge in the 0.10 and 0.20 mgal contours in the area east of Pacoima Reservoir (figure 3) is also partially indicated by the elevation changes measured in Little Tujunga and Big Tujunga Canyons (shown in parentheses in figure 3, indicating that elevation changes were converted to equivalent gravity changes). Because the elevation changes in this area are relative to 1929 levels and because the northward swing is contrary to the general pattern of vertical displacement determined for a dislocation model (Savage and others, this Bulletin, figure 7), the elevation change may include pre-earthquake secular uplift due to gradual elastic loading between 1929 and 1970. However, the gravity changes in the area east of Pacoima Reservoir are relative to initial gravity measurements in 1964 and 1970 and, if anything, are larger than the 1929-based, gravity-converted elevation changes (figure 3), suggesting that most of the uplift between Pacoima Reservoir and Big Tujunga Canyon probably took place at the time of the earthquake and not during the preceding 40 years.

One intriguing possibility suggested by the gravity data is that local decreases in elevation were effected by the earthquake. Two areas of possible elevation decrease (areas of positive gravity changes) are located in the mountain range both northeast and northwest of the maximum observed gravity decreases (figure 3). These data are less precise (±0.10 mgal) than most of the values obtained in other areas from the gravity remeasurements, but seven of the values are larger than the estimated error and thus are probably significant. The largest measured gravity increase

(+0.31 mgal), located about 1 km northwest of Pacoima Reservoir (figure 3), implies an elevation decrease, using equation (2), of (−4.5) (0.31) or about −1.4 m. Savage and others (this Bulletin) report local slumping in the vicinity of this point as well as an anomalous horizontal displacement (see station Mesa, their figure 7). The amount of slumping was estimated by Savage (oral communication, 1972) to have been about 0.7–1.0 m based on the combined heights of three fresh scarps located within 100 m north of the station. If this estimate is correct, it is reasonable that about +0.2 mgal of the +0.31 mgal gravity change is due to surficial land motion and that only the difference of about +0.1 mgal can be attributed to regional tectonic movement at the time of the earthquake. This corrected determination of regional increase at Mesa is consistent with increases of +0.02 to +0.14 mgal determined at six nearby stations. A vertical-angle remeasurement of elevation is available at just one of these stations, that at May (figure 3), which shows a decrease in elevation since 1935 of −0.2 ± 0.4 m (J. C. Savage, oral communication, 1972).

Another geodetic application of measuring gravity changes is evident in the long distance over which the relative vertical movements can be easily determined. In this study, we not only know that there was essentially no vertical movement of the central part of San Fernando Valley relative to UCLA within the limits of our remeasurements (±0.04 mgal or the elevation-equivalent of ±0.18m), but we are also reasonably sure that UCLA has not moved vertically between 1965 and post-earthquake 1971 relative to our prime base for California at the USGS offices in Menlo Park, some 320 miles north. If there were any question about a possible coincidental subsidence of Los Angeles Basin and San Francisco Bay, extensive gravity calibration runs between Menlo Park and such distant points as Mt. Hamilton, Sentinel Dome in Yosemite Park, and Mt. Lassen indicate no significant vertical movement since 1962 (Oliver, 1969). Our measurements indicate that during this period there was no gravity change and probably no significant vertical movement of San Fernando Valley south of the rupture zone relative to Los Angeles Basin and to the specified mountains of central and northern California.

EVIDENCE FOR SUBSURFACE MOVEMENTS

That the ratio of the gravity changes to elevation changes in northern San Fernando Valley falls along the Bouguer gradient instead of the free-air gradient (figure 4) means that in some way mass was *added* beneath the gravity stations; that is, the uplift did not take place by a simple vertical expansion of the northern block.

Independent evidence supporting this conclusion comes from the study of water levels in wells within the area of uplift, for, if a dilatation of the ground occurred north of the fault, the water levels should have dropped due to the volume expansion. Observations of this phenomenon are numerous for the case of tidal deformation (Melchior, 1966, chapter 6). In the uplifted area north of the Sylmar fault segment (figure 3), most of the water levels remained the same (±1 m) relative to the ground surface, according to pre- and post-earthquake records of the Los Angeles Flood Control District (C. C. Green, written communication, 1971). Monthly records for two of these wells are plotted in figure 5; the locations of the wells are shown on the gravity change map (figure 3).

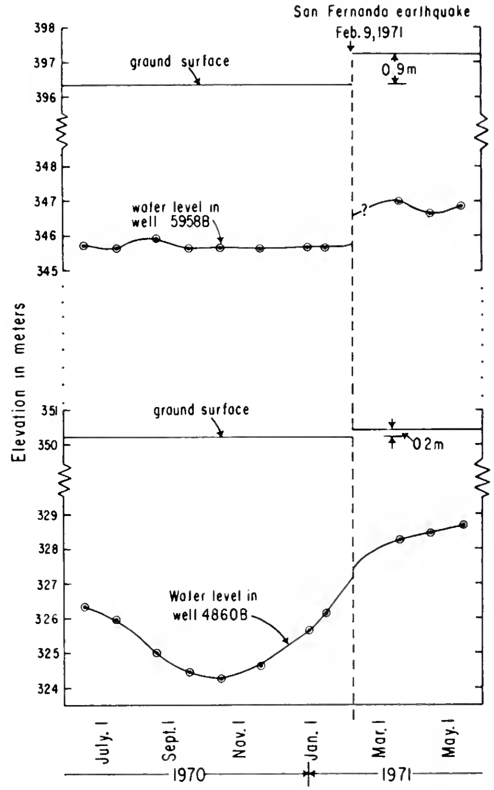


Figure 5. Relation of changes in the water table to changes in surface elevation at two wells in Sylmar basin within area of uplift. Locations of wells shown on figure 3; projected location of well 55958B on A–A′ indicated on figure 6. Monthly measurements of water levels made by the Los Angeles County Flood Control District (C. C. Green, written communication, 1971); change in surface elevations interpolated from releveling data of Burford and others (1971).

Corrections for the surface uplift have been made and the data indicate that the water level, particularly in well 5958B, moved upward about the same amount as the surface, as if it were confined in a rigid block. In other parts of the disturbed area, Proctor (personal communication, 1972) reported dramatic drops of 10–30 m in five wells north of the Tujunga segment of the fault in Kagel Canyon (figure 3); and it may be more than coincidence that our one observation of

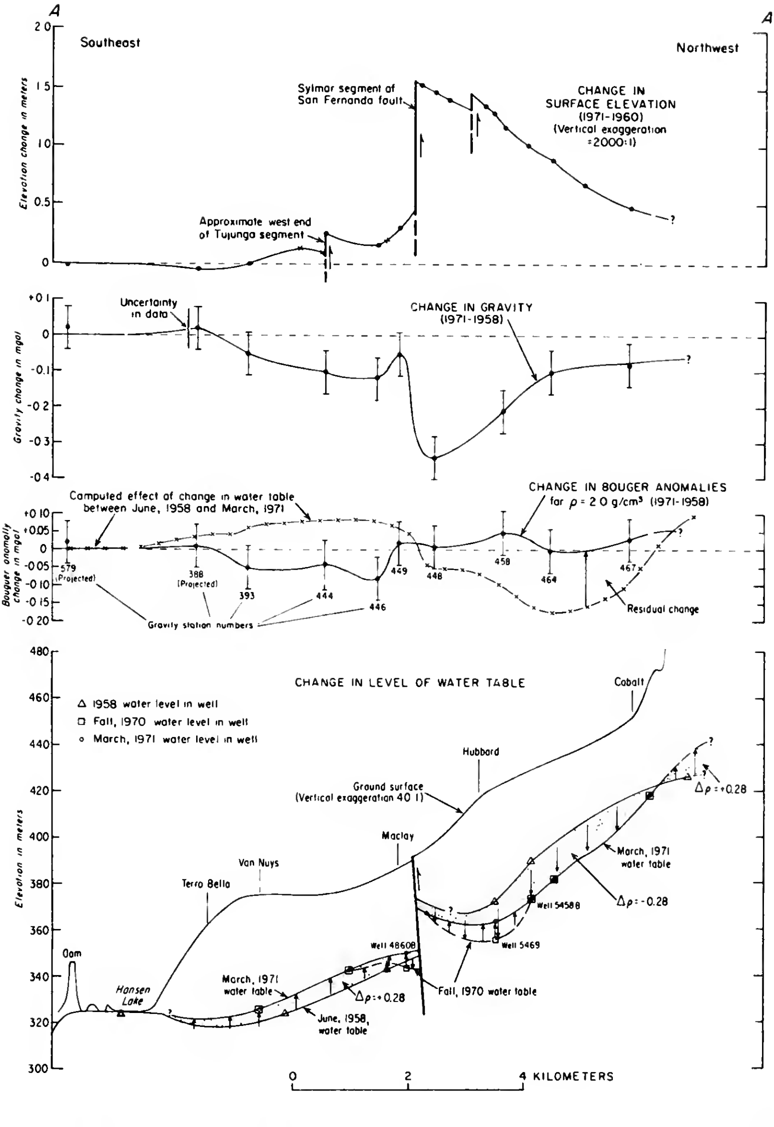


Figure 6. Profile A–A′ along Foothill Boulevard (see figure 3) showing the relation between changes in surface elevation, gravity, Bouguer gravity anomalies, and level of water table. Measurements of elevation both before the earthquake (1960) and after (1971) made relative to "Tidal 8" bench mark in San Pedro by the City of Los Angeles (R. Agronti, written communication, 1971). "Change in surface elevation" profile includes data from Burford and others (1971), distinguished by crosses, and a local theodolite remeasurement of Corbato's station 444 by R. Alewine. The uncertainties in the gravity and Bouguer anomaly changes (±0.06 mgal) are shown to help visualize the various curves permitted by the data. Changes in Bouguer anomalies are reduced assuming that surficial material involved in changes in elevation has a density of 2.0 g/cm³ (see table 1). The model used to compute the effect on gravity of change in level of water table between 1958 and 1971 shown by stippled area and based on a 1958 contour map prepared by the California State Water Rights Board (1962, plate 30); well data for 1970 and 1971 provided by the Los Angeles County Flood Control District (C. C. Green, written communication, 1971); water levels in wells within 1 km of A–A′ projected along the water table surfaces for 1958, 1970, and 1971.

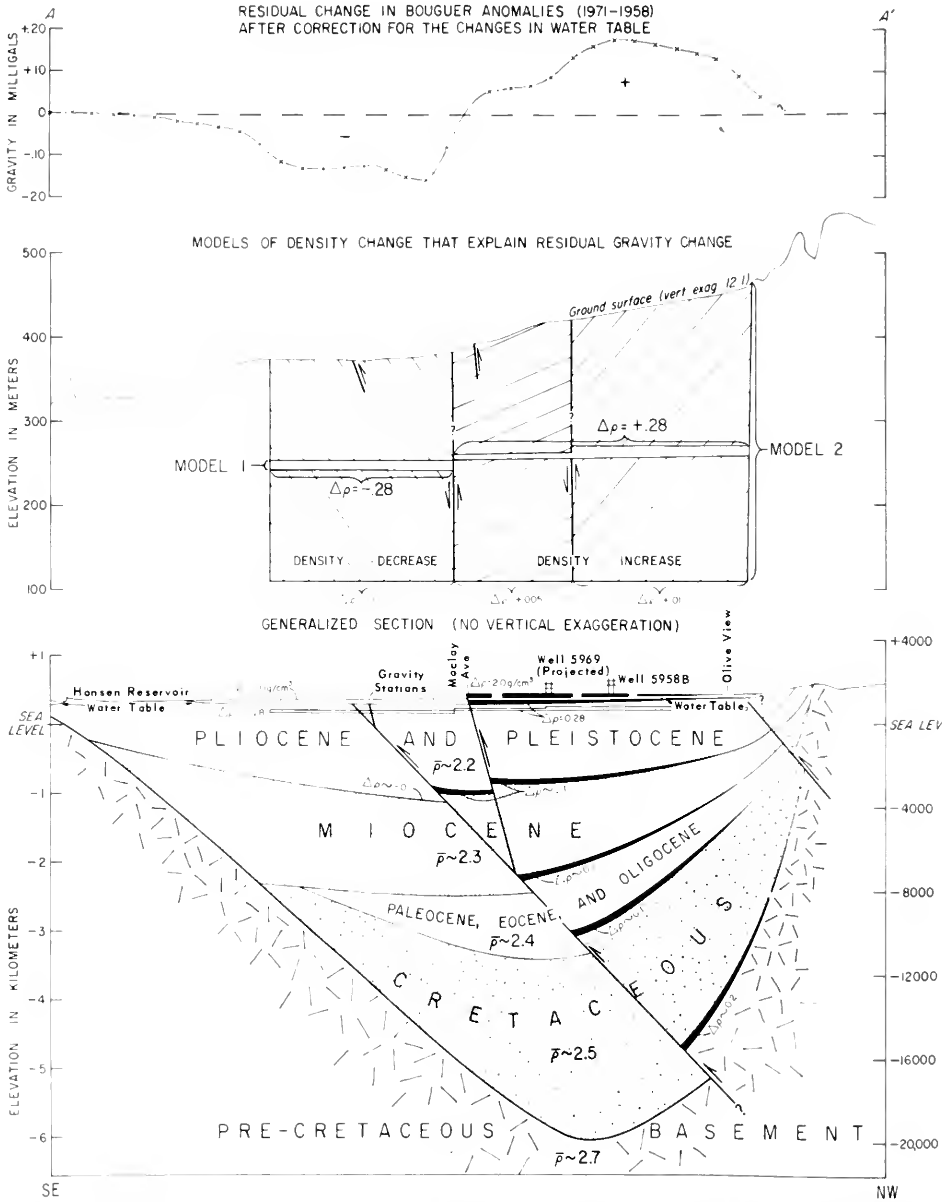


Figure 7. Residual gravity change along A–A′ (see figure 3), interpreted models of density change, and generalized geologic section. Model 1 assumes that the implied decrease in density south of the Sylmar rupture and an increase north of the rupture is concentrated along a thin (~10 m) layer having negative and positive density contrasts, respectively, of 0.28 g/cm³. In model 2, the vertical extent of density changes has been expanded to the surface. Generalized geologic section based on Nagle and Parker (1971, figures 13 and 18) and on Wentworth and Yerkes (1971, figure 2). Geologically reasonable mass movements which may have contributed to the change in gravity at the time of the earthquake indicated by shaded wedges and exaggerated for clarity. Corresponding estimates of the density contrast ($\Delta\rho$ in g/cm^3) introduced by these movements are shown.

gravity change in the Kagel area, station 559, plots midway between the slopes corresponding to free-air and Bouguer gradients (figure 4). Some dilatation may have occurred locally, but the evidence from both gravity and water level changes indicate that most of the thrust sheet moved as a rigid block and added mass to the area.

Evidence for the manner in which mass was added comes from the analysis of change in Bouguer anomalies. The changes can be interpreted using the same methods as the interpretation of Bouguer anomalies themselves. In this case, detailed measurements along Foothill Boulevard (figure 6) show that the decrease in gravity of 0.34 mgal north of the Sylmar segment of the fault is nearly nullified by making a correction for the vertical movement of the station (free-air effect) and the attraction of the material making up the elevation change, assumed to have a density of 2.0 g/cm³ (Bouguer correction). We are able to explain most of the gravity change by a simple stacking of surficial layers, having a density approximately that of alluvium, on the pre-earthquake surface level.

Although the changes in Bouguer anomalies—gravity changes corrected for changes in surface elevation—are small (.08 mgal or less), they do form a pattern of gradually increasing negative changes north of Hansen Reservoir and then rising abruptly at station 449, just south of the Sylmar rupture and remaining slightly positive northward as far as Olive View. Although the data for any given point have a statistical uncertainty of ±0.06 mgal, most of the points are probably good to 0.02–0.03 mgal as suggested by the continuity of the pattern itself. To understand these data, we need to consider what subsurface mass changes might have taken place between the initial gravity measurements in 1958 and post-earthquake 1971.

The most obvious change in mass—and the only one for which any data are available—is due to water table fluctuation. Water levels in selected wells have been measured in the northern San Fernando Valley by the Los Angeles County Flood Control District since 1928; these records (mostly unpublished) show that the water table is at a depth of 30 to 50 m and has been dropping steadily since about 1950. Figure 8 shows this drop in a well located just north of the Sylmar rupture where the gravity decreased about 0.26 mgal (#5969 in figure 3). In this well, the water level had dropped about 15 m between 1958 and the fall of 1970 and then rose an anomalously large 8 m between October 1970 and March 1971, leaving a net change of about —9 m between the times that the two sets of gravity measurements were made. Assuming a 28 percent porosity for the alluvium at a depth of about 50 m—a porosity that corresponds to the measured saturated density of 2.2 g/cm³ (Corbato, 1963, figure 6) and a grain density of 2.67 g/cm³—the effect on gravity of the 9-m drop in water level is about —0.11 mgal, using an infinite sheet approximation for the water table. This gravity effect is obviously significant, being slightly larger than the largest change in Bouguer anomalies observed along section A-A′ (—0.08 mgal at station 446). Thus, some attempt at correcting the change in Bouguer anomalies for the change in level of the water table is necessary.

Unfortunately, most of the water wells near Foothill Boulevard for which 1958 water levels are available were subsequently closed off by a court decision, and for both 1958 and 1971 measurements at only two

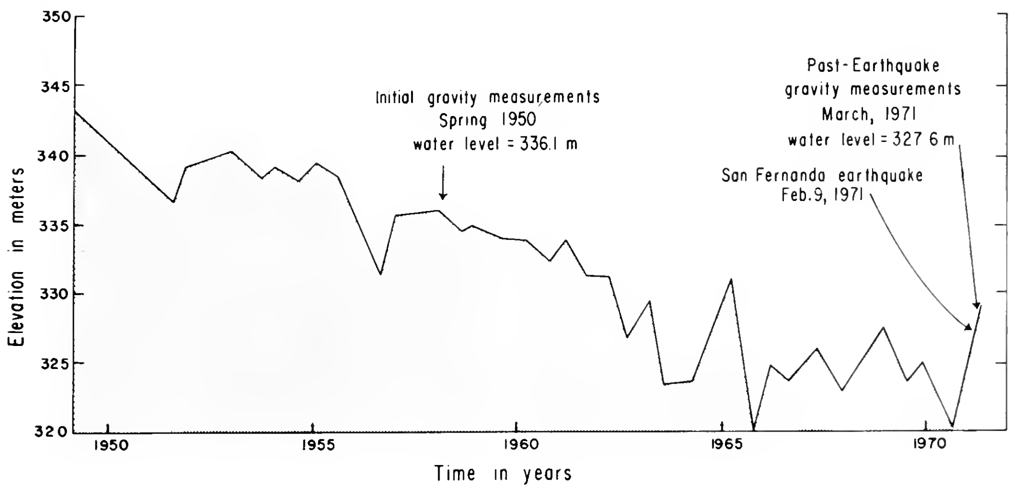


Figure 8. Change in water level in well 5969 between 1949 and 1971 (after Madrid, 1972, plate 2). Well located just north of Sylmar rupture and about 0.3 km west of Foothill Boulevard (figure 3). Projected location of well shown on geologic section (figure 7) where surface uplift was about 1.3 m. Pre-earthquake elevation of surface 379 m.

wells within 1 km of Foothill Boulevard are available (figure 6). An *accurate* calculation of the gravity change expected from the change in level of the water table is impossible. However, a rough two-dimensional model of the water table changes along A-A′ from 1958 to 1970 to 1971 has been made in figure 6 by taking differences along the profile between a 1958 contour map prepared by the California State Water Rights Board (1962, plate 30) and another contour map for fall 1970 made by the Los Angeles City Department of Water and Power. The fall 1970 profile (figure 6) has been updated to March 1971 using seven well measurements (circled dots in figure 6) made available by the Los Angeles County Flood Control District. The levels in five of these wells did not change more than 2 m between fall 1970 and spring 1971, an example being well #5958B, the monthly data for which is shown in figure 8. By contrast, both wells #4860B and #5969 on opposite sides of the Sylmar rupture had large seasonal variations; the variation of 4½ m at #4860B was gradual and did not result from the earthquake effects, except for perhaps 0.2 m, the amount of surface uplift (figure 5).

The surprising part of the change in water table between 1958 and 1971 is the rise of 3 to 6 m south of the Sylmar rupture. This result was unsuspected because of the decrease in Bouguer anomalies over the same area. Moreover, the decrease in gravity of —0.15 mgal 2 miles south of Van Norman Reservoir (figure 3) is consistent with a lowering of the water level of about 8 m between 1958 and 1970. Perhaps the rise south of the Sylmar rupture, if real, is a result of diffusion of water from Hansen Reservoir, which has been intermittently filled since 1952. In any case, the abrupt drop in water table in the vicinity of the Sylmar rupture seems to be adequately documented, and we have computed the gravitational effect of the water level changes shown by the stippled area (figure 6). The computation was done on an IBM 360/65 computer using a U.S. Geological Survey modification of Talwani's two-dimensional program (Talwani and others, 1959). The results of the computation are plotted at horizontal intervals of about 0.22 km (crosses in figure 6) and indicate that the effect of the change in water table is indeed of the same order of magnitude as the change in Bouguer anomalies, but of opposite sign, being positive south of the Sylmar rupture and negative to the north.

The residual gravity change (that is, the difference between the computed effect of the change in water table and the change in Bouguer anomalies) is illustrated in figure 7 (upper profile). We wish to stress the uncertainties in this profile, the parent anomaly change itself being largely statistically insignificant. However, we believe that the general form of the residual is significant and that it poses a curious constraint on dislocation models of subsurface movements associated with the San Fernando earthquake. We have sketched two subsurface models of density changes (figure 7) which generally satisfy the gravity residual and make some intrinsic sense but which are difficult to reconcile with the expected density changes based on published concepts of subsurface movements as illustrated in the generalized section (figure 7).

In model 1, a decrease in density of 0.28 g/cm³ of a 10-m-thick plate of material at a depth of about 120 m is invoked, together with a similar density increase to the north of the fault in the form of a step. The step could either be geometric (as pictured) or in the density increase. Geologically, model 1 could result from a 10- to 12-meter lowering of a perched water table south of the fault combined with the steplike rise to the north but could not result from just displacements of beds with different densities associated with reverse faulting. The effect is too large to be explained by a movement of only 2 m by a series of beds whose total integrated contrast is limited to about $2.7 - 2.2 = 0.5$ g/cm³. Model 1 is also shown in the generalized section at true scale.

Model 2 is also not very appealing geologically. It represents the other end of a mathematical bracket wherein a minimum change in density contrast of 0.01 g/cm³ is assumed to have taken place throughout the upper 250 m of material, the change again being negative to the south and positive to the north of the Sylmar rupture. A density change of 0.005–0.010 g/cm³ implies a strain release of $2 - 4 \times 10^{-3}$ and could conceivably occur in the upper 300 m of material depicted in figure 7 as the result of strain relaxation associated with elastic rebound; but again, the expected change from elastic rebound is in the wrong direction, being negative to the north of the fault (see Savage and others, this Bulletin, figure 3). We are not satisfied with the residual change and the models (figure 7) and hope that additional data being obtained will help clarify the problem. As an alternative, for example, if the residual gravity low south of the Sylmar rupture is not real and better data demonstrate that the horizontal extent of gradients at the edges of the anomalies are larger, then the gravity high to the north of the fault can be explained in terms of the displacements of the bottom 1 to 2 m of beds by higher density material beneath as indicated schematically by the shaded wedges in the generalized section (figure 7).

CHANGE IN THE STATE OF ISOSTATIC BALANCE

The state of isostatic balance of the San Gabriel Mountains is not well known nor is its nature understood. Some degree of regional balance is indicated by a northeastward decrease in Bouguer gravity anomalies, which generally corresponds to an increase in the average elevation of topography (Gilluly and others, 1968, figures 10–15). The general level of Bouguer anomalies in the area of the gravity change (figure 3) is —70 to —80 mgal (Corbato, 1963, Map 2), and these values are reduced to isostatic anomalies of 0 to —20 mgal, depending on the depth of compensation and the isostatic system assumed in the reduction (Duerksen, 1949, station numbers 246, 314 and 315). Grannell and Biehler (1971) have reported more detailed gravity measurements showing that the mountains have little effect on this regional gravity gradient, implying that there is no local mountain root beneath the San Gabriel block. This conclusion is supported by the interpretation of seismic data from the Cannikan explosion (Mellman, 1972) but in disagreement with the interpretation of seismic refraction and reflection data of Roller and Healy (1963, figure 10), who concluded that a normal 30-km crust beneath Los Angeles thickens to about 40 km beneath the San Gabriel Mountains. Interpretation of Roller and Healy's seismic data is inconclusive as to the completeness of compensation.

Whatever state of compensation existed before the earthquake, it is clear that the region of uplift and gravity change (figure 3) is now slightly heavier. Average free-air anomalies are regarded as one measure of isostatic compensation; in this case, free-air anomalies increased algebraically by an amount equal to the negative of the difference in slopes between the free-air gradient (— 0.309 mgal/m) and the least-squares fit of the changes in gravity to the change in elevation data (— 0.215 mgal/m) times the elevation change (ΔE) at any station; that is, $0.094\Delta E$. This simple formula, of course, is an approximation and subject to the same local variations as the residual changes in the Bouguer anomalies, which average about +0.1 mgal over the area of uplift between the Sylmar fault segment and Olive View (figure 7). If we take $\Delta E = 1$ m as the average value of the uplift in area, the average free-air anomaly increased about *0.2 mgal.*

Isostatic anomalies did not increase as much. They are determined by adding the gravitational effect of some perfectly compensating mass system to Bouguer anomalies. The changes in isostatic anomalies associated with the earthquake (ΔIA_i) are the sums at various locations (i) of the residual changes in Bouguer anomalies (ΔBA_i) plus the effect of changes in a compensating model necessary to support the added mass (ΔIC_i); that is,

$$\Delta IA_i = \Delta BA_i + \Delta IC_i.$$

As we have seen in the previous section, ΔBA_i is positive north of the Sylmar segment, negative to the south, and nowhere exceeds 0.18 mgal (figure 7). ΔIC_i was obtained by assuming an Airy-Heiskanen scheme of compensation for a crustal thickness of $T = 20$ km—this will give a maximum estimate (see Oliver, 1960)—and adding an increment of crustal thickness of $(2.67/0.6)\ \Delta E_i$ or a maximum of about 10 m on to the bottom of the presumed mountain root. For a two-dimension approximation, the calculation reduces to measuring a series of plane angles ($\Delta\Theta$) subtended at the earth's surface by a series of semi-infinite horizontal slabs, and using the relation

$$\Delta IC_i = 2\pi\gamma\Delta\varrho\Delta H(\Sigma\,\Delta\Theta_i/180) \text{ gals}$$

where $\gamma = 6.67 \times 10^{-8}$ cgs

$\Delta\varrho$ = assumed density contrast between the crust and upper mantle in g/cm^3

ΔH = thickness of the slab in cm

Using $\Delta\varrho = 0.6$ g/cm^3 and $\Delta H = 1$ m, this form reduces to

$$(0.0258/180)\sum_{i=1}^{10}\Delta\Theta_i \text{ mgal}$$

where Θ_i is in degrees. For the mirrored geometry of uplift along A-A′ at a depth of 20 km (figure 3) $\Sigma\Theta_i$ directly above the compensating mass is 110°, $\Delta\Theta$ varying from 3° to 30°. Thus the maximum change in isostatic correction, $\Delta IC_{max} = (.0258)(110)/180 \sim$ *0.02 mgal.* Additional angular measurements show that the effect drops off very slowly to the north or south, becoming about half at a horizontal distance of 15 km. The effect of increasing the crustal thickness to $T = 40$ km is to decrease the attraction by about 20 percent (0.004 mgal). The change in isostatic anomalies within the area of uplift is largely determined by the change in Bouguer anomalies, but a small positive change of 0.01 mgal extends over much of the San Gabriel block.

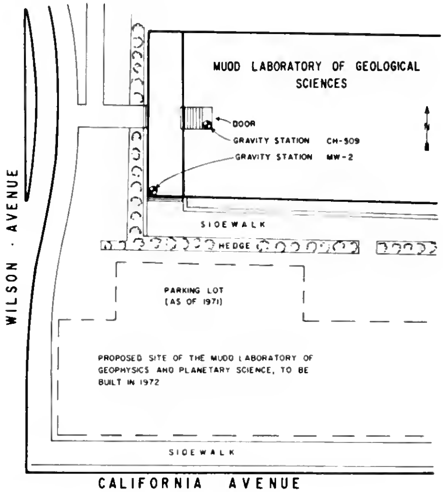
The above analysis quantifies the conclusion that additional mass was introduced (probably from the north) that has not yet been compensated. Some of the additional mass may be effectively compensated by the two areas of positive gravity change (figure 3) which indicate a drop in elevation from mass removal. The axis of maximum gravity increase forms an inverted "U" and is partially coincident with the northern limit of the area of aftershocks (figure 2). This relation supports the conclusion of Wesson and others (1971) that the envelope of aftershocks represents the edge of a dislocated thrust sheet. Mass removal and subsidence could be expected at the northern edge of the southward-moving sheet similar to the formation of a bergschrund as glaciers pull away from their immobile ice adhering to the headwall of a valley. Perhaps further adjustments, not necessarily in our lifetime, may provide information on the state of compensation of the San Gabriel block. For example, if the southern part of the San Gabriel Mountains had been in perfect isostaric balance before the earthquake, we would expect the block, in the absence of other tectonic forces, eventually to sink partly back toward its pre-earthquake level by an amount $\varrho_1 h/\varrho_2$, where ϱ_1 is the average density of the thrust plate, ϱ_2 the density of whatever substratum is buoying up the mountain range (upper mantle?), and h the average change in elevation of the uplifted area. Using $\varrho_1 = 2.67$ g/cm^3, $\varrho_2 = 3.27$ g/cm^3, and $h = 1$ m, the present uplifted surface would need to sink *0.82 m* to regain its former state of balance. Partial fall-back has been observed in connection with other earthquakes. A striking example is the 1960 Chilean earthquake, where a shoreline was raised 1½ m and subsequently dropped about 70 percent of the previous rise to about ½ m five months after the earthquake (Saint-Amand, 1961, p. 16).

If the San Gabriel block was overcompensated prior to the earthquake, as is more likely the case judging by geologic evidence for the recency of large vertical movements—these movements predominate for the last five million years—one would expect the block to continue rising by a series of discontinuous events. On the other hand, if the mountains north of San Fernando are undercompensated, one would expect the area to be sinking, which is contrary to geologic evidence, and moreover to continue sinking more than the 0.82 m calculated above for return to a state of isostatic balance.

GRAVITY STATION # MW-2

NAME Cal Tech	STATE California
LATITUDE 34° 08.19'	LONGITUDE 118° 07.59'
ELEVATION 762±5 ft.	
OBSERVED GRAVITY 979578.90 mgal	DATE March 18, 1971

LOCATION DESCRIPTION: California Institute of Technology, near the southwest corner of Mudd Laboratory of Geological Sciences on the east side of Wilson Avenue about 50 yds. north of its intersection with California Avenue, over a painted red spot about 2 inches in diameter on tiled surface at west end of top of 4 steps leading under south archway to cloistered hallway. Station is about 5 ft. lower and 2 archways south of another Cal Tech base described by Chapman (1966, p. 25, no. 309).



Looking south from west entrance to Mudd Laboratory

Looking northwest from sidewalk south of Mudd Laboratory

Figure 9. Principal facts, description, sketch map, and pictures showing location of base station MW-2 at California Institute of Technology. Similar information is available at CDMG offices for all stations listed in table 1 (Robbins and others, 1972).

Isostatic forces probably play a secondary role in the tectonic movements of the San Gabriel block, the primary role being thought by many geologists to be a horizontal north-south compression with the Transverse Ranges acting as a buttress beneath which a southern coastal plate is being thrust (Wentworth and Yerkes, 1971, p. 6). Perhaps the measurement of future gravity changes in this area would help resolve some of these questions and provide added evidence of subsurface movements. To this end, we have prepared detailed descriptions, sketch maps, and/or pictures of the 87 gravity stations listed in table 1 and recommend that most of these stations be remeasured every *two years* to monitor future changes. Figure 9 is an example of these station descriptions and describes the primebase MW-2 at the California Institute of Technology. This material is on file at the offices of the California Division of Mines and Geology and the U.S. Geological Survey (Robbins and others, 1973.)

CONCLUDING REMARKS

The San Fernando earthquake presented the best opportunity we have had for studying the relation between changes in gravity and elevation as extensive measurements had been made in this metropolitan suburb. The ΔG–ΔE plot in figure 4 shows convincingly that the gravity changes are related to the elevation changes by a Bouguer gradient rather than a free-air gradient. The linearity of the relation $\Delta g = -0.215\Delta E \pm 0.026$ at San Fernando indicates that gravity can probably be used in future earthquakes to outline rapidly an area of elevation change relative even to points as much as 1000 km away if the change is greater than ± 0.3 m. This method could be most important in a very large earthquake.

The detailed measurements along Foothill Boulevard (figure 6) place serious constraints upon subsurface movements attributed to the reverse-oblique faulting recognized at the surface. These constraints are made somewhat uncertain by the lack of accurate knowledge of ground water changes between 1958 and 1971; but, in general, we believe that the tectonic movements involved the addition of mass to the area and that most of the gravity change was caused by a simple stacking of surficial layers on the pre-earthquake surface level, as might be expected in thrust faulting.

Between the Sylmar fault segment and Olive View Hospital, there is a curious relation between the loss in mass associated with the withdrawal of ground water since about 1950 and the excess mass now imposed on the pre-earthquake surface. *They are nearly equal;* that is, the addition of mass at the time of the earthquake (top curve, figure 6) in a sense compensates isostatically for the loss of water mass subtracted by pumping (stippled area, bottom section, figure 6). This relation must be fortuitous, for the maximum withdrawal was only about 25 m (figure 8); at 28 percent porosity, this amounts to a water column only 7 m thick. Moreover, the withdrawal of water under Burbank, in the southern part of San Fernando Valley, has been significantly greater (California State Water Rights Board, 1962, plate 31) and no major earthquakes are known to have occurred there. If a region is already strained by vertical extension nearly to the point of rupture, a slight reduction in load such as the lowering of the water table by 25 m could conceivably trigger the rupture.

Gravity might be a useful tool for monitoring the water table where inadequate well data are available, as well as for rapidly detecting vertical movements and subsurface mass changes. About 14,000 new gravity stations were established in 1968–70 throughout California at intervals of 2 to 5 miles (Chapman, 1969; Oliver, 1969; Rietman, 1969); 20 to 50 percent of these stations are reoccupiable to within 0.1 m vertically and 1 m horizontally (equivalent to a repeatability of $\pm .03$ mgal). This study, along with Barnes' (1966) work on the Alaskan earthquake, indicates a need for accurate, reoccupiable gravity stations in other seismically active regions throughout the world.

ACKNOWLEDGMENTS

We wish to thank C. E. Corbato and J. F. Long for providing detailed description of their original gravity measurements. Professor Corbato also recalculated the observed gravity values to the nearest 0.01 mgal for his stations listed in table 1. The U.S. Geological Survey and the University of California at Riverside field teams benefited from the help of R. F. Sikora and S. W. Smith, respectively. The Long Beach State University field teams were aided by J. F. Long, W. Anthony, W. Biggs, and S. Piatt. Extensive hydrologic data on San Fernando Valley were furnished by the Los Angeles County Flood Control District through C. C. Green of their Los Angeles office. We have benefited by consultations with R. J. Proctor, Metropolitan Water District of Southern California, and Carlos Madrid, California Department of Water Resources, on the effect of the earthquake on water levels. Ralph Agranti, City of Los Angeles, Bureau of Engineering, provided the detailed leveling data along Foothill Boulevard shown in figure 6. The field measurements and reductions made by R. Alewine for this report were supported by the National Science Foundation grant GA 29920. J. C. Savage, R. O. Burford, and W. T. Kinoshita made available their paper on geodetic measurements published in this Bulletin. We wish to especially thank R. F. Yerkes, who served as our geologic consultant throughout the interpretation of the data.

CHAPTER 17

Magnetic Anomalies and Active Faults in the San Fernando Area

by Rodger H. Chapman[1] and Gordon W. Chase[1]

Magnetic observations in the northern part of the San Fernando Valley by the California Division of Mines and Geology show that faults that displaced Quaternary alluvium during the earthquake of February 9, 1971, are commonly marked by magnetic anomalies. These anomalies are probably caused by abrupt changes in thickness of the alluvium and possibly by the presence of other magnetite-bearing rocks in the vicinity of the fault zones.

In this part of the San Fernando Valley area, the alluvium is derived in large part from igneous rocks which crop out in the San Gabriel Mountains to the north and east (Oakeshott, 1958, p. 117). Some of these igneous rocks, which range in composition from anorthosite and gabbro to granite, contain a significant amount of magnetite-ilmenite; thus the alluvium may have a relatively high magnetic susceptibility in comparison to most of the Tertiary and Quaternary sedimentary rocks with which it is in contact in this area. Certain other sedimentary rocks, particularly the Pleistocene Saugus Formation, may also contain a relatively high proportion of magnetite-ilmenite.

Because of the association of magnetic anomalies and faults in the San Fernando area, magnetic methods were used by the Division of Mines and Geology to guide additional geophysical work and augment geologic mapping, especially in parts of the area where surface breaks did not occur during the recent earthquake. This report is a brief summary of the initial results of the geophysical measurements.

FIELD WORK

Field measurements consisted of one or more lines of magnetometer readings oriented approximately normal to the trend of the known or suspected faults under investigation. Station spacings generally were at intervals of from 50 to 100 feet. The measurements were taken with either an Askania vertical-intensity magnetic balance with a sensitivity of about 10 gammas per scale division or a Jalander vertical-intensity fluxgate magnetometer with a reading accuracy of about 10–15 gammas.

In some parts of the San Fernando Valley area the usefulness of ground magnetic measurements is limited by the presence of various man-made structures containing iron or steel. Particularly common are urbanized areas with associated utility lines, reinforced-concrete highways, canal linings, bridges, railroads, pipelines, transmission towers, and culverts. Some of these structures disturb the magnetic field for horizontal distances of several hundred feet. An attempt was made to avoid such magnetic disturbances; but, even in areas that were believed to be relatively free of these effects, unknown buried metallic objects probably contribute to the "noise" seen in the results.

AREAS STUDIED

Little Tujunga Canyon

In Little Tujunga Canyon, the San Fernando fault zone is marked by two prominent fault scarps which formed in the February 9, 1971, earthquake. The southernmost scarp, or Tujunga segment, showed a vertical displacement of 40 to 50 cm.; the northern most scarp, or Lakeview segment, showed a displacement of 20 to 50 cm. (Barrows and others, 1971).

Line A-A′, plate 3 and figure 1, is a short, east-trending line which crosses the Quaternary alluvium in the canyon and is close to outcrops of Tertiary sedimentary rocks (Modelo Formation) on both sides of the wash (Oakeshott, 1958, plate 1). This line is included to show the magnetic effect of the alluvium. Although the data are characteristically "noisy", the magnetometer profile shows a distinct positive anomaly which corresponds to the location of the stream wash. The amplitude of this anomaly probably represents, in a general way, the thickness of alluvium

This paper was presented by Dr. Chapman at the annual meeting of the Society of Exploration Geophysicists, held at Anaheim, California, November 26–30, 1972. It has been released for publication by the Editor of *Geophysics*.

[1] Geophysicists, California Division of Mines and Geology, Sacramento.

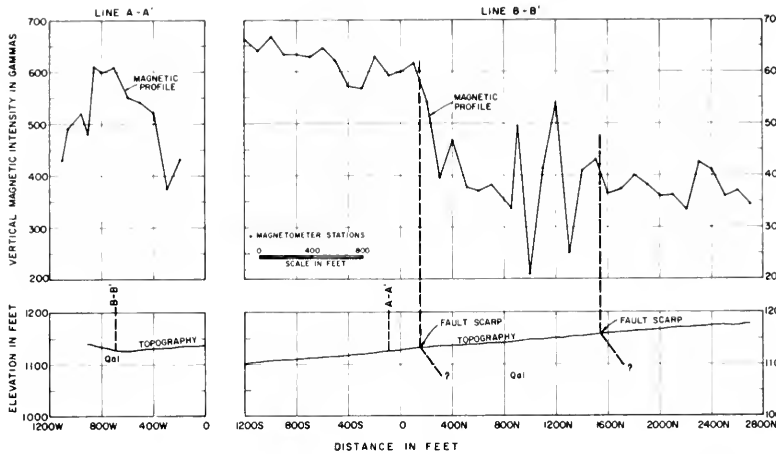


Figure 1. Vertical intensity magnetic profiles A–A′ and B–B′ (arbitrary datum), Little Tujunga Canyon, San Fernando area, California.

present along this particular cross section of the wash.

Line B-B′, plate 3 and figure 1, is a line which follows the gently sloping wash, upstream in a north to northeast direction, and crosses the traces of both faults mentioned above. The magnetic profile shows many irregularities, most of which are probably caused by variations in the concentration of natural magnetic material in the alluvium. The most notable feature of this profile, however, is the steep magnetic gradient located close to the position of the Tujunga segment scarp. This gradient appears as a step in the profile (downward to the north) with a magnitude of about 200 gammas. Whether or not an anomaly is associated with the trace of the Lakeview segment on this profile is difficult to determine because of the level of the background "noise".

According to R. J. Proctor (written communication, 1971) seismic profiles in the vicinity of the Tujunga segment scarp in Little Tujunga Canyon show a layer with a velocity of 8000 feet per second at a depth of about 12 feet, just north of the scarp, and a layer with a velocity of 6500 feet per second at a depth of about 50 feet, south of the scarp. There is also a ground water "cascade" or change in ground water level at about the same location (California State Water Rights Board Report, 1962, v. 1, plate 30).

Tujunga Canyon-Lakeview Area

East of Lakeview Terrace Sanitarium, the surface rupture which represents the Lakeview segment of the San Fernando fault zone curves southward into Big Tujunga Wash, then follows the northern edge of the wash in a general direction somewhat north of east. Plate 3 shows the location of four preliminary north-trending magnetometer lines, C_1–C'_1, C_2–C'_2, C_3–C'_3, C_4–C'_4, located about half a mile east of Lakeview Terrace Sanitarium. In this area, Barrows and others (1971) have recorded a vertical displacement on the south-facing scarp in the range of 55 to 80 cm. Magnetic profile C^4-$C^{4\prime}$ (figure 2) shows a steep gradient close to the location of the known fault trace which results in an abrupt increase in the magnetic field of about 300 gammas from north to south. Profiles C_1–C'_1, C_3–C'_3 are east of and parallel to C_4–C'_4. Each of these profiles also shows a steep magnetic gradient; however, the position of the anomaly apparently diverges southward from the mapped scarp from west to east. This suggests that if the anomaly is caused by a buried fault scarp, the surface ruptures during the recent earthquake did not follow the older, or at least most prominent, fault zone in this direction (see plate 3).

The results of seismic work in the area near profile C_4–C'_4 by Proctor (written communication, 1971), indicate a layer with a velocity of 8000 feet per second at a depth of about 16 feet to the north of the fault scarp, and a layer with the same velocity, at a depth of about 24 feet, south of the scarp. If the magnetic susceptibility of the alluvium were approximately constant throughout the area, one would expect the size of the observed anomaly to be roughly proportional to the fault displacement in the alluvium. In a comparison between the results obtained in Little Tujunga Canyon and Big Tujunga Wash, however, the reverse is observed: The anomaly in Big Tujunga Wash is the larger of the two, but the change in thickness of alluvium (from seismic data) is smaller. This is evidence that the effective magnetic susceptibility (hence, magnetite content) of the alluvium varies appreciably from one place to another as might be expected.

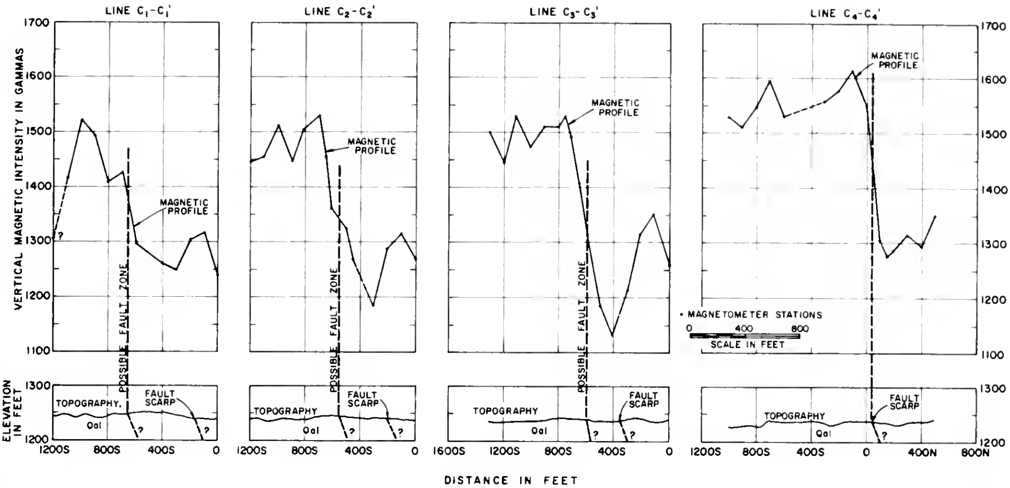


Figure 2. Vertical intensity magnetic profiles C_1–C'_1, C_2–C'_2, C_3–C'_3, C_4–C'_4 (arbitrary datum), Big Tujunga Canyon, San Fernando area, California.

Magnetometer lines located in Big Tujunga Wash east of the eastern end of the mapped tectonic breakage failed to provide evidence for any subsurface continuation of the fault zone in this direction.

The Veterans Fault

In the northern part of the San Fernando Valley near the foothills of the San Gabriel Mountains, there was extensive damage to structures as a result of the February 9 earthquake; but there is only one known tectonic surface break between the Golden State Freeway, on the west, and Pacoima Wash on the east (U.S. Geological Survey, staff, 1971, p. 71). This break, the Veterans fault, is located mainly in a partially completed housing subdivision east of the U.S. Veterans Hospital and west of Pacoima Wash (Burrows and others, 1971). North of the fault are found exposures of the Pleistocene Saugus and Pacoima Formations; south of the fault, terrace deposits (older Quaternary alluvium, see plate 2).

A series of four short, closely spaced magnetometer lines J_1–J'_1, J_2–J'_2, J_3–J'_3, and J_4–J'_4 (plate 3 and figure 3) was obtained over the fault break in an unfinished part of the subdivision east of Rajah Street. Three of these four profiles are marked by very distinct magnetic anomalies, or sharp breaks in the profiles, with amplitudes of between 100 and 200 gammas each, located close to the known position of the fault. On these profiles the magnetic field increases from the Pacoima Formation on the north side of the fault to alluvium on the south side. The south end of the fourth profile, J_3–J'_3, is apparently disturbed by a magnetic anomaly caused by metallic objects near Tucker Street.

Magnetometer lines were run both east and west of the known surface break of the Veterans fault. Lines in Pacoima Wash, to the east, show no evidence for an extension of the fault in this direction. Furthermore, no surface breaks were found in the alluvium in this area following the February earthquake to suggest a hidden fault zone (Barrows and others, 1971). To the west, magnetic anomalies which may represent a continuation of the fault were found on a line along Loop Canyon crossing Hubbard Street (west of Candlewood Drive), and on lines northeast of Simshaw Street, south of the Veterans Hospital (lines K, L, and M, plate 3 and figure 3). Although work is still incomplete in this area, the anomalies are evidence that the Veterans fault continues from the mapped break in a direction just south of west through a field below the Veterans Hospital (see plate 3). From this area, it may continue into the housing subdivision southwest of Simshaw Street.

The Veterans fault anomaly appears to increase from approximately 100 gammas in amplitude at the eastern end of the mapped surface break (line J_1–J'_1) to about 200 gammas on the Loop Canyon line (K) and to nearly 300 gammas on the lines south of the Veterans Hospital (lines L and M). This may indicate a westward increase in either the offset on the fault or in the contrast in magnetic susceptibility. The large amplitude of this anomaly, which is comparable to that found on the Tujunga and Lakeview fault segments, suggests that the Veterans fault is also a significant structural break which must have a history of movement in Holocene geologic time.

If there is a significant western extension of the Veterans fault zone, as suggested by the present work, tectonic activity along this zone could explain the notable damage which occurred at the Veterans Hospital, even though no tectonic surface breaks have been mapped in this area. In the area west of the Veterans Hospital, no magnetic anomalies, which could

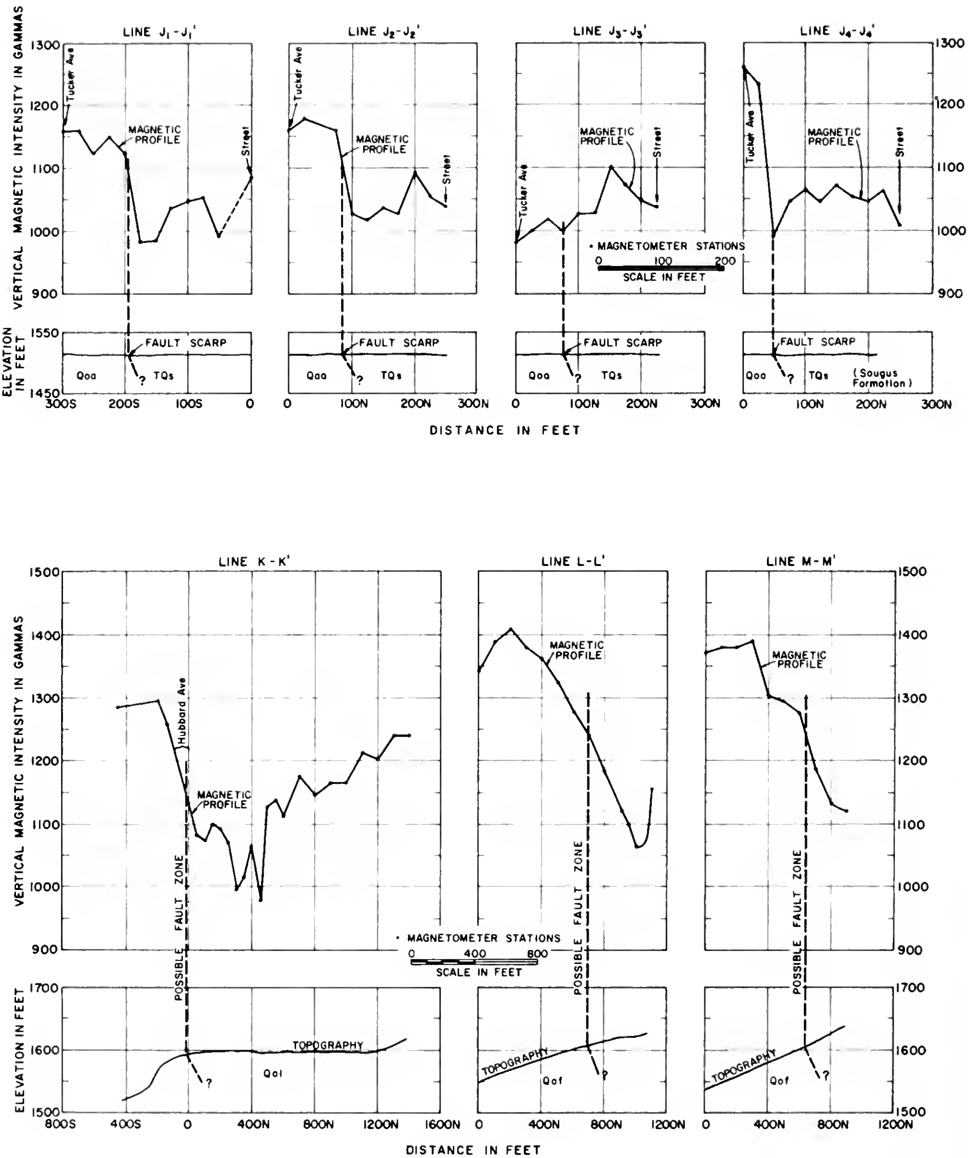


Figure 3. Vertical intensity magnetic profiles J_1–J'_1, J_2–J'_2, J_3–J'_3, J_4–J'_4, K–K', L–L', M–M', (arbitrary datum) Veterans fault, San Fernanda area, California.

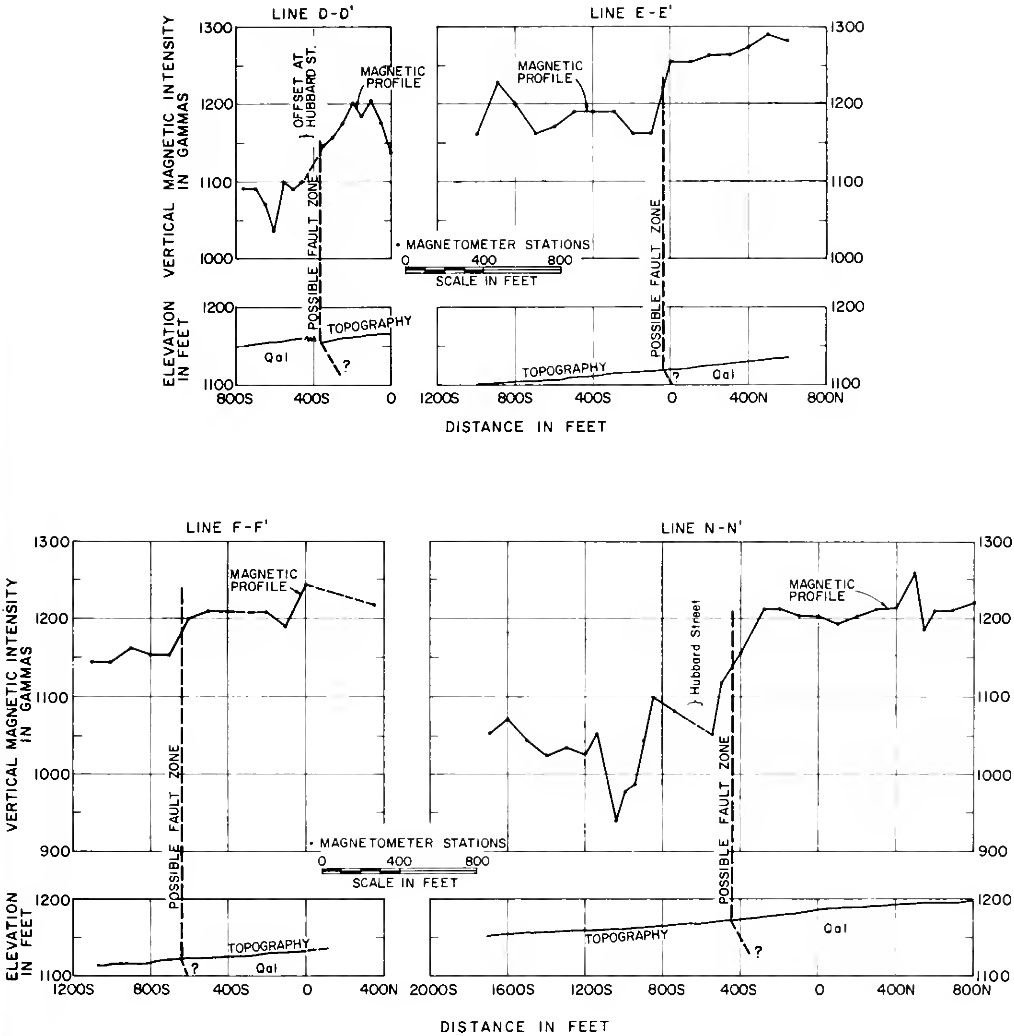


Figure 4. Vertical intensity magnetic profiles N–N′, D–D′, F–F′, E–E′ (arbitrary datum) Mission Wells-Sylmar fault segments, San Fernando area, California.

represent a continuation of this zone, have yet been identified on the few magnetometer lines available (plate 3).

The Mission Wells and Sylmar Fault Segments

The Mission Wells and Sylmar fault segments are both located chiefly in the relatively flat part of San Fernando Valley at some distance from the foothills. Because most of this area is within subdivisions of the City of San Fernando, it proved to be one of the more difficult places in which to obtain useful magnetic data. For example, near city streets the readings were affected by numerous buried utility lines and in Pacoima Wash, south of Lopez dam, the data were unreliable because of the presence of fences and a reinforced concrete ditch lining near the location of the fault break. The only data utilized in this area were obtained in the few fields and open spaces that could be found.

Although surface breaks related to the recent earthquake are not continuous between the Mission Wells and Sylmar segments of the fault, these two segments may represent one fault zone, continuous at depth, which is also a ground water barrier in this area (Wentworth and Yerkes, 1971, p. 13), (California State Water Rights Board, 1962, v. 2, figure A-1). Drill hole data suggest that the alluvium in the area generally between the two fault segments is thicker than that in the vicinity of the surface breaks, and this may represent a buried drainage system, called the Sylmar "notch", where it crosses the ground water barrier (California State Water Rights Board, 1962, v. 2, p. 15). Two magnetometer lines (E–E′ and F–F′, plate 3) were run in an open field just northeast of San Fernando Road beyond the easternmost end of the ground breakage associated with the Mission Wells segment of the fault; one short line (D–D′, plate 3) was located in small fields northeast of Herrick Avenue near the intersection with Hubbard Street, and another line (N–N′) was located parallel to and just southwest of Glen Oaks Boulevard near the intersection with Hubbard Street. Profiles E–E′ and F–F′ (figure 4) show relatively small but distinct magnetic anomalies, or gradients, which appear as steps, 60 to 80 gammas in amplitude, close to the projected extension of the Mission Wells surface ruptures. Line F–F′ may contain more than one step. Similarly lines D–D′ and N–N′ (figure 4) show distinct magnetic anomalies each with amplitudes of more than 100 gammas. The steep gradient in each case is near a line projected between the Mission Wells and Sylmar fault segments. In these examples, however, the anomalies are reversed; that is, the level of the magnetic field is higher on the north, presumably upthrown, side of the projected fault. The reason the usual magnetic anomaly relationship is not observed on these lines is unknown; however, a possible cause may be found in the local geologic setting. The Pleistocene Saugus Formation north of the fault zone in this area is overlain by only a shallow cover of alluvium, but south of the fault Tertiary sedimentary rocks are overlain by a much thicker layer of alluvium (California State Water Rights Board, 1962, v. 2, p. 15). It may be that the gravels which characterize the Saugus Formation are more magnetic in the area north of the fault than is the alluvium south of the fault, especially if the alluvium in this part of the valley contains less magnetite than is found closer to the mountain fronts. Measurements of the magnetic susceptibility of samples of these sedimentary units might resolve this problem. Whatever the true cause of these anomalies, however, the results tend to confirm the possible continuity of the fault between the Mission Wells and Sylmar surface breaks.

Olive View-Juvenile Hall Area

A number of magnetometer lines were located both east and west of the Olive View Hospital and near Juvenile Hall in an attempt to identify possible faults in this area near the mountain front. These lines show no major anomalies near Olive View Hospital or Juvenile Hall which might suggest important faults, even though earthquake damage in these locations was severe. However, two nearly parallel lines G–G′ and H–H′, west of the Olive View Hospital, do show an anomaly of possible significance (plate 3 and figure 5). These lines extend generally southward from near the alluvium-Pacoima Formation contact at the base of the San Gabriel Mountains. Most of the magnetometer stations were located in olive groves and were relatively free from spurious magnetic effects, but some were affected by utility lines and highways. In order to eliminate the most obvious irregularities, a "smoothed" version of each profile (dotted line) is also shown in figure 5.

South of Foothill Boulevard, both lines show very distinct anomalies, each consisting of a positive-negative pair with a peak-to-peak amplitude of from 150 to 200 gammas. The positive anomalies are on the south side on both profiles.

The causes of these observed anomalies are not known, but the characteristics of the anomalies indicate a source no deeper than a few hundred feet. Therefore, they do not originate in the basement rocks, which are believed to be at a depth of several thousand feet in this area (California State Water Rights Board, 1962, v. 1, plates 5 and 5B). Offset of alluvium, or of some other relatively magnetic rock along a fault zone, is a possible cause for these anomalies; a dipping magnetic layer or bed is another.

Magnetometer lines southwest of G–G′ and H–H′ show some indication that the trend of this anomaly may continue southwestward, perhaps at least as far as San Fernando Road near the junction with Olden Street. On the other hand, a northeast continuation has not been identified with certainty from limited work done between lines G and H and the Olive View Hospital.

Assuming that the anomalies are caused by a fault, the approximate location of this possible fault is shown on the profiles (figure 5) and on plate 3. It may be significant that this location is somewhat south of, but nearly parallel to, that given for the Olive View fault proposed by Merifield (1958) and also shown on the Los Angeles sheet of the Geologic Map of California (Jennings and Strand, 1969). Additional geophysical data and possibly subsurface data will be needed to identify more clearly the source of this anomaly.

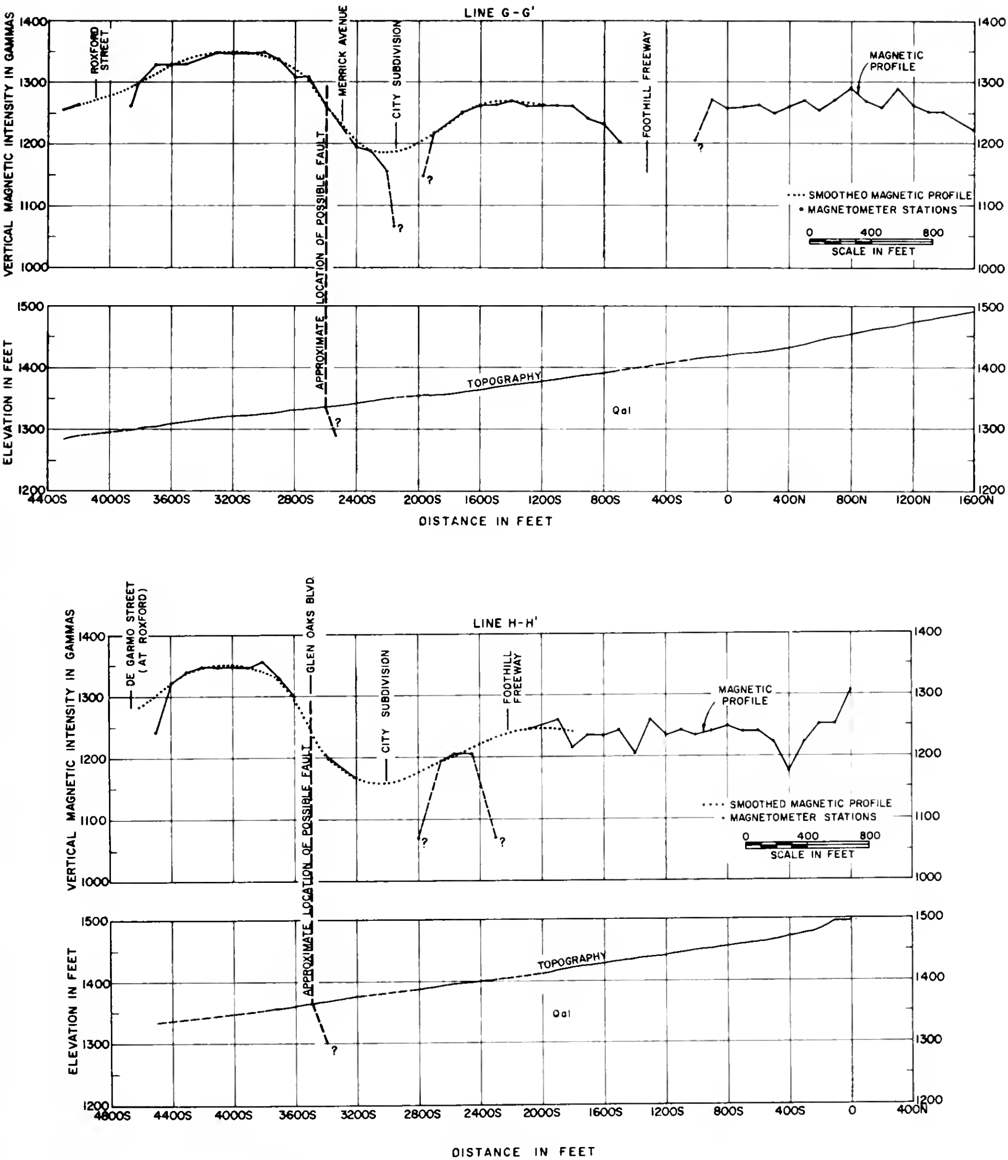


Figure 5. Vertical intensity magnetic profiles G–G', H–H' (arbitrary datum), Olive View, San Fernando area, California.

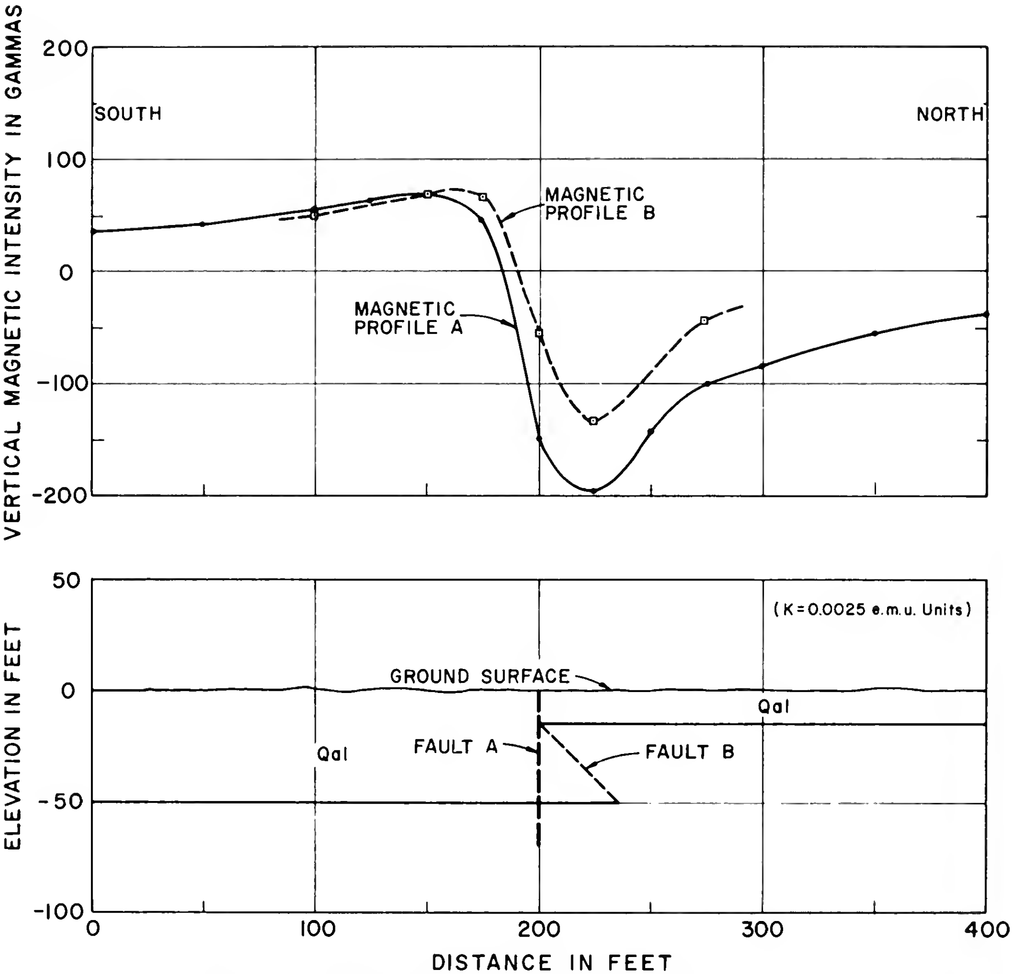


Figure 6. Theoretical vertical intensity magnetic anomalies for faulted sheets.

DISCUSSION AND CONCLUSIONS

The magnetometer observations in the San Fernando Valley area discussed above show that distinct magnetic anomalies are associated with traces of some of the known active faults where the faults cross alluvium or other magnetite-bearing rocks. These magnetic anomalies are apparently most often caused by the abrupt thickening of the alluvium on the downthrown side of the fault. In effect, the anomalies represent fault scarps which have been preserved by burial in the alluvium.

The theoretical anomaly to be expected on a line crossing a faulted magnetic bed can be calculated by means of the expressions given by Heiland (1946, p. 395, 397). For example, curve A, figure 6, shows the vertical intensity anomaly calculated for a vertically faulted bed about 35 feet thick, buried at a depth of 15 feet, assuming an effective magnetic susceptibility of 0.0025 emu. This example approximates the displacement indicated by seismic work in Little Tujunga Canyon. The strike of the edge of the bed is assumed to be approximately magnetic east. Because the active faults we are concerned with in the San Fernando Valley are probably reverse or thrust faults, curve B, figure 6, is given to show a comparison with the case of a fault surface dipping at an angle of 45° to the north. As shown in figure 6, the theoretical curve for the reverse or thrust fault has a less steep magnetic gradient over the fault and a less pronounced magnetic minimum. In actual examples, however, this distinction may be difficult to recognize. The magnetic susceptibility used for the theoretical profiles, 0.0025 emu, was chosen to produce an anomaly approximately the same size as those actually observed, but no magnetic susceptibility measurements have been made on samples. This value is somewhat high even considering the types of igneous rocks present in the alluvium, so it may be that the actual fault displacement in this example should be greater and the magnetic susceptibility correspondingly less.

Some of the observed magnetic profiles in the San Fernando area show a distinct resemblance in shape to the theoretical profiles in figure 6 (see figures 2 and 3); however, in other examples the anomalies are distorted, partly because of "noise," and topographic effects, and variations in thickness and magnetic susceptibility of the alluvium. Therefore, the most easily recognized feature of these fault-line anomalies in most cases is probably the steep magnetic gradient which should be located close to the fault zone.

If the alluvium were fairly uniform in magnetic characteristics, it might be possible to estimate the relative displacement of a buried fault by the amplitude of the magnetic anomaly. However, as mentioned above in comparison of results at Little Tujunga Canyon and Lakeview Terrace Sanitarium, the size of the anomaly did not correlate with displacement as shown by seismic measurements. It is likely that the magnetite content of the alluvium, hence magnetic susceptibility, varies widely throughout the area.

Although it was found difficult to estimate fault displacement from the amplitude of a magnetic anomaly, the observed anomalies do indicate that the cumulative displacement on many of the faults is considerably greater than that resulting from the most recent episode of fault movement. Furthermore, in some places the observed anomalies suggest extensions of fault zones that apparently did not cause surface ruptures in the recent earthquakes.

The use of surface magnetic measurements is limited in much of the San Fernando Valley area by the presence of man-made structures and materials; however, data analysis techniques and possibly continuous-recording mobile ground or low-level airborne magnetometers might be useful in eliminating some of the undesirable magnetic effects in future work.

SUPPLEMENT

Additional geophysical data were obtained in the San Fernando area in order to provide more information on some of the fault zones discussed in the first part of this report. Most of these data are the results of magnetic surveys, but some represent tests by seismic and gravity methods.

MAGNETIC DATA

Tujunga Canyon-Lakeview Area

New magnetic profiles were obtained both east and west of lines C_1-C_1' and C_4-C_4' (plate 3 and figure 2) along the surface breaks associated with the Lakeview segment of the fault. As indicated in the first part of this report, the magnetic anomaly that is associated with the fault in this area apparently diverges southward from the surface rupture of the fault east of line C_4-C_4'. As can be seen on plate 3, this anomaly trend may represent an extension of a branch of the Lakeview segment of the fault that did not cause a surface rupture during the recent earthquake. East of line C_1-C_1', however, the magnetic gradient characteristically associated with the fault is less steep and covers a wider area, as indicated on line C_6-C_6' (plate 3 and figure 7). This relatively broad gradient may represent the combined effects of more than one fault in this part of the area. Further east, as shown by line C_7-C_7' (plate 3 and figure 7), the usual steep magnetic gradient is once again present—now directly over the surface rupture of the Lakeview segment near the north end of the profile.

Line C_{13}-C_{13}', located about a quarter of a mile east of the Lakeview Terrace Sanitarium (plate 3 and figure 8), crosses the surface breaks of the southern branch of the Lakeview segment of the fault in Big Tujunga Wash. This profile is also marked by a distinct magnetic anomaly over the fault zone, which suggests a pronounced subsurface displacement. Westward from line C_{13}-C_{13}', the mapped surface breaks on the branch of the fault in Big Tujunga

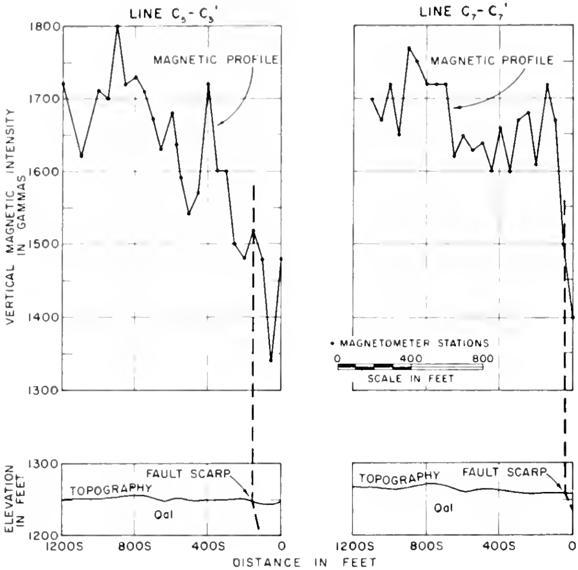


Figure 7. Vertical Intensity magnetic profiles C_5-C_5' and C_7-C_7' (arbitrary datum), Big Tujunga Wash, San Fernando area, California.

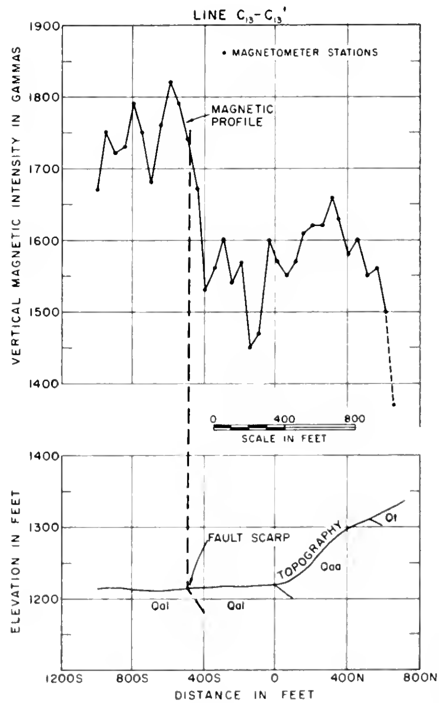


Figure 8. Vertical intensity magnetic profile C_{13}-C_{13}' (arbitrary datum), Big Tujunga Wash, San Fernando area, California.

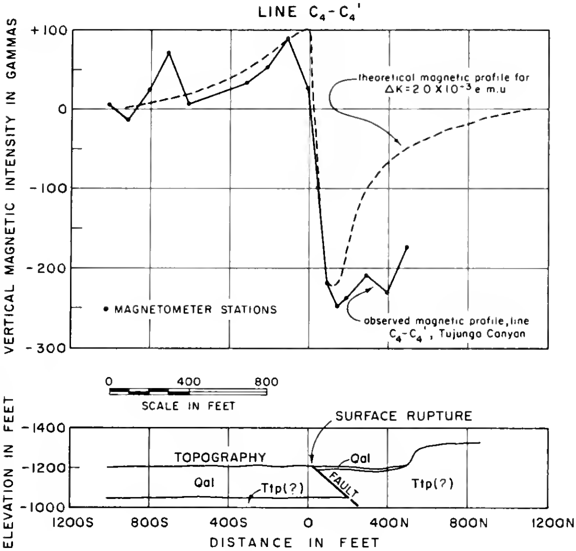


Figure 9. Vertical intensity magnetic profile C_4-C_4' and theoretical anomaly for faulted sheet, Big Tujunga Wash, San Fernando area, California.

Wash end east of the Lakeview Terrace Sanitarium (plate 3). For more than a mile and a half in this direction—between the sanitarium and the apparent end of the Tujunga fault segment east of Little Tujunga Canyon—there are no mapped surface breaks along the northern edge of the Wash. Although no magnetometer data are available in the area, the large magnetic anomalies at Little Tujunga Canyon on the west and the sanitarium on the east suggest a possible continuous fault segment between these two areas.

Figure 9 is a comparison of the magnetic anomaly actually observed on line C_4-C_4' in Big Tujunga Wash with a theoretical anomaly calculated by means of the expression given by Heiland (1946, p. 397) for a magnetic slope. The slope of the fault surface is assumed to be 45° north. The alluvium was assumed to be approximately 150 feet thick south of the fault and about 15 feet thick north of the fault on the basis of a drill hole in Oliver Canyon, west of this area, that showed terrace deposits displaced at least this much (Proctor and others, 1972, p. 1611). The theoretical anomaly also assumes a contrast in magnetic susceptibility of 0.002 emu/cm^3 between the alluvium and the underlying rocks. Except for the north end of the profile in this example, the theoretical anomaly approximates the observed anomaly reasonably well. Although no attempt has been made to measure the magnetite content of the alluvium in this area, the calculated magnetic susceptibility would probably correspond to a difference in the average magnetite content of roughly 1 to 2 percent.

The Veterans Fault

Additional magnetometer lines were added south and east of the Veterans Administration Hospital in order to examine in more detail the anomaly in this area, which was discussed on page 215. Line R_8-R_8' (plate 3 and figure 10) crosses this anomaly in an open field below the hill east of the Veterans Administration Hospital. The hill in the northern part of this area may cause some distortion of the magnetic field; however, the amplitude of the anomaly is more than 400 gammas on this line. Thus, if this anomaly is caused by a fault, it is one of the larger such anomalies found thus far in the San Fernando area.

The anomaly south of the Veterans Administration Hospital was traced westward part way across the open field (line R_4-R_4', plate 3 and figure 10), where the anomaly either bends toward the southwest or is offset in this direction. If it does continue in this direction, it enters a city subdivision, where it was not possible to continue detailed magnetic work.

SEISMIC AND GRAVITY DATA

To determine the possible usefulness of other geophysical methods for tracing the "active" fault zones in the San Fernando area, a few detailed seismic refraction and gravity profiles were made in parts of the area. For the seismic profiles, a 12-channel Midwestern portable seismic refraction unit was used. Energy was supplied by a 300-pound weight that was dropped along a track to strike a steel plate on the ground. The geophone cables used were 220 and 550 feet long with a corresponding geophone spacing of 20 and 50 feet. Shot points were taken at each end and at the center of each geophone cable and, in some cases, at offset locations beyond the end of the cable. The gravity data were obtained by means of a Worden gravimeter with a scale constant of approximately 0.10 milligals per scale division.

A seismic profile (not shown) crossing the Tujunga segment of the fault near magnetic line B-B' (plate 3 and

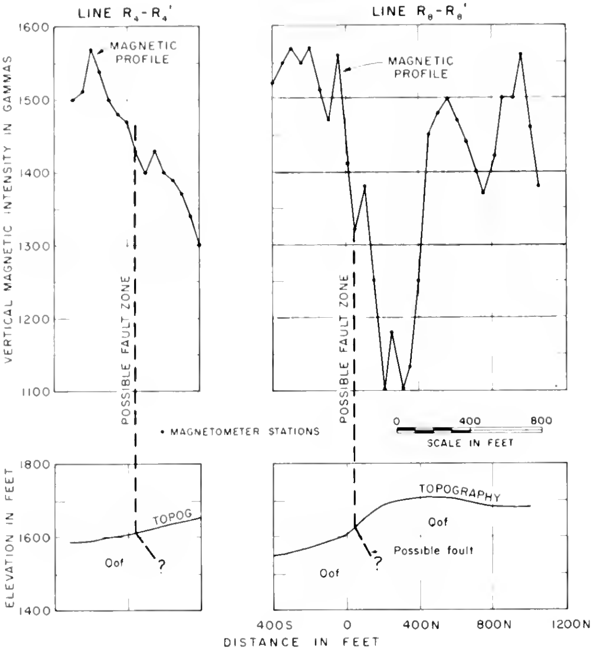


Figure 10. Vertical intensity magnetic profile R_4-R_4' and R_8-R_8' (arbitrary datum), Veterans fault, San Fernando area, California.

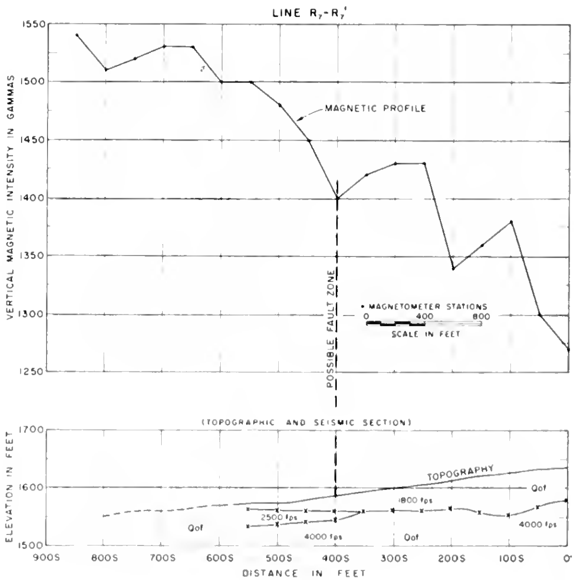


Figure 11. Vertical intensity magnetic profile R_7-R_7' (arbitrary datum) and seismic refraction section, Veterans fault, San Fernando area, California.

figure 1) yielded data that was very similar to that reported by Proctor (1972, p. 1616). North of the surface break, the interface between layers having velocities of approximately 1000 and 8000 feet per second was found at a depth of about 8 feet. South of the surface break, layers characterized by velocities of approximately 1500, 3300, and 8000 feet per second were found at depths of 5, 21, and 51 feet, respectively. Thus, the high velocity layer is apparently offset vertically over 40 feet along the fault in this area.

Figure 11 shows line R_7-R_7', a seismic and magnetic profile, located south of the Veterans Administration Hospital area and just west of the southern part of line R_8-R_8' (plate 3). The seismic profile is 550 feet long and crosses the location of the possible fault shown on line R_7 and plate 3. This profile fails to show evidence of significant fault displacement of the deepest layer detected (approximately 4000 feet per second). It does show a layer with an intermediate velocity (2500 feet per second) present on the south end of the seismic profile that apparently pinches out near a possible fault. If such a fault is present, as suggested by the magnetic data, it might not have been detected because of the limited depth of penetration of the seismic energy. Alternatively, the magnetic anomaly may have a cause other than faulting, perhaps a contact between two rock units such as older alluvial fan deposits and the Saugus Formation that may have similar seismic velocities but different magnetic susceptibilities.

Figure 12 is a gravity profile on line B-B′, which crosses the Tujunga segment of the San Fernando fault in Little Tujunga Canyon. This corresponds to a part of magnetic profile B-B′ (figure 1). The gravity data are Bouguer anomalies calculated for an assumed density of 2.67 g/cm^3. Although the gravity profile is characterized by a relatively steep gradient downward to the north, which is believed to represent an anomaly on a regional scale, there is no evidence of a local anomaly in the vicinity of the Tujunga segment of the fault. Other gravity profiles in this area also failed to show any features that could be interpreted as fault-related anomalies. It is likely that the explanation for the lack of gravity anomalies over these fault zones is the relatively small difference in density between alluvium and the older Quaternary and Tertiary rock units offset by the fault.

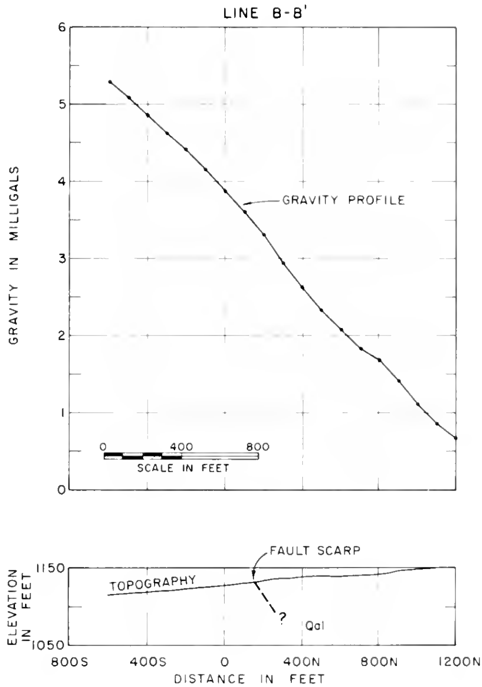


Figure 12. Bouguer gravity profile B-B′ (arbitrary datum), Little Tujunga Canyon, San Fernando area, California.

Afterslip on the Sylmar Fault Segment[1]

by A. G. Sylvester [2] and D. D. Pollard [2]

ABSTRACT

A series of first-order precision levelings of two 200 m long lines shows that more than 6 mm of vertical afterslip occurred in the period from 4 to 330 days following the main shock of the 1971 San Fernando earthquake. This is only about 1 percent of the total vertical component of slip measured at the site shortly after the earthquake, and it is negligible compared with afterslip documented for other recent California earthquakes at Parkfield in 1966 and at Borrego Mountain in 1968.

These data suggest that the available stored elastic strain energy may have been completely released throughout the rupture volume during the main earthquake and main aftershocks, so that there was little or no residual strain to be relieved by afterslip. Experimental studies of rock deformation suggest that this mechanism of strain release is probably typical of crustal blocks capable of supporting high normal stresses and separated by "compressional" types of faults like the thrust fault responsible for the 1971 San Fernando earthquake.

Detailed geodetic studies following some recent California earthquakes have shown that displacement may continue at the fault trace for many months after the main shock (Wallace and Roth, 1967; Smith and Wyss, 1968; Scholz and others, 1969; Burford, in press). Typically, the rate of the displacements decreases logarithmically with time, corresponding to a similar decrease in the frequency of aftershocks. Nason (1969) termed this phenomenon "afterslip" and noted that the number of documented cases is small. The displacements following the 1966 Parkfield earthquake were episodic with no obvious direct relationship between local seismic activity and afterslip (Smith and Wyss, 1968; Scholz and others, 1969); however, it is not clear if this is typical and can be expected for all earthquakes.

The location, rate, and duration of the displacements may provide important information for understanding the mechanisms of earthquakes and aftershocks (Nason, 1971); but the information is likely to be of equal importance to engineers involved in reconstruction of pipelines, streets, bridges, and buildings across the traces of surface ruptures in residential and commercial areas.

The purpose of this study was to determine if afterslip occurred on part of one of the main surface ruptures in Sylmar and, if so, to attempt to determine its rate and relationship to aftershocks.

PROCEDURE

An X-shaped figure was established and surveyed on 13 February 1971 (PST) across the central part of the Sylmar fault segment (U. S. Geological Survey, 1971) where the zone of surface rupturing is relatively narrow and well defined (figure 1). Initial horizontal and vertical components of slip were determined from displaced sidewalks and curbs and amounted to nearly 2 m and ¾ m, respectively (Kamb and others, 1971; U. S. Geological Survey, 1971). Several extension fractures broke Cometa Avenue between our Points A and IP (figure 1). Each fracture extended into private yards on each side of the street for unknown distances and exhibited from 1 to 5 cm of vertical displacement and from 0 to 2 cm of right-lateral displacement.

Each monument is an 8-cm PK nail driven into the 15-cm thick asphalt street until the base of the head was flush with the surface of the street. Care was taken to locate the points in parts of the street which we guessed (and hoped) would survive the inevitable excavation of damaged underground utility lines and as far as possible from fresh cracks. The nearest crack

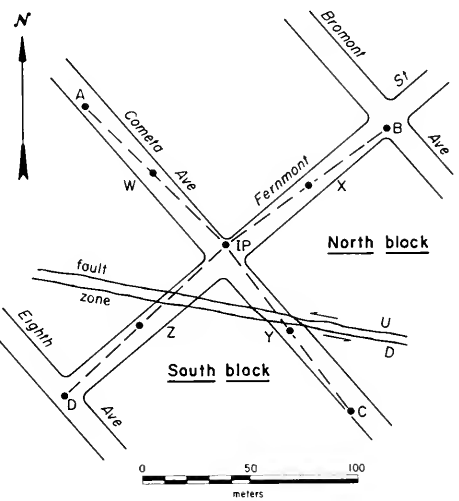


Figure 1. Index map showing plan of U.C.S.B. geodetic strain array across part of the Sylmar fault segment.

[1] U.C.S.B. Marine Science Institute Contribution No. 7. Manuscript submitted for publication January 31, 1972.

[2] Marine Science Institute and Department of Geological Sciences, University of California, Santa Barbara, California 93106.

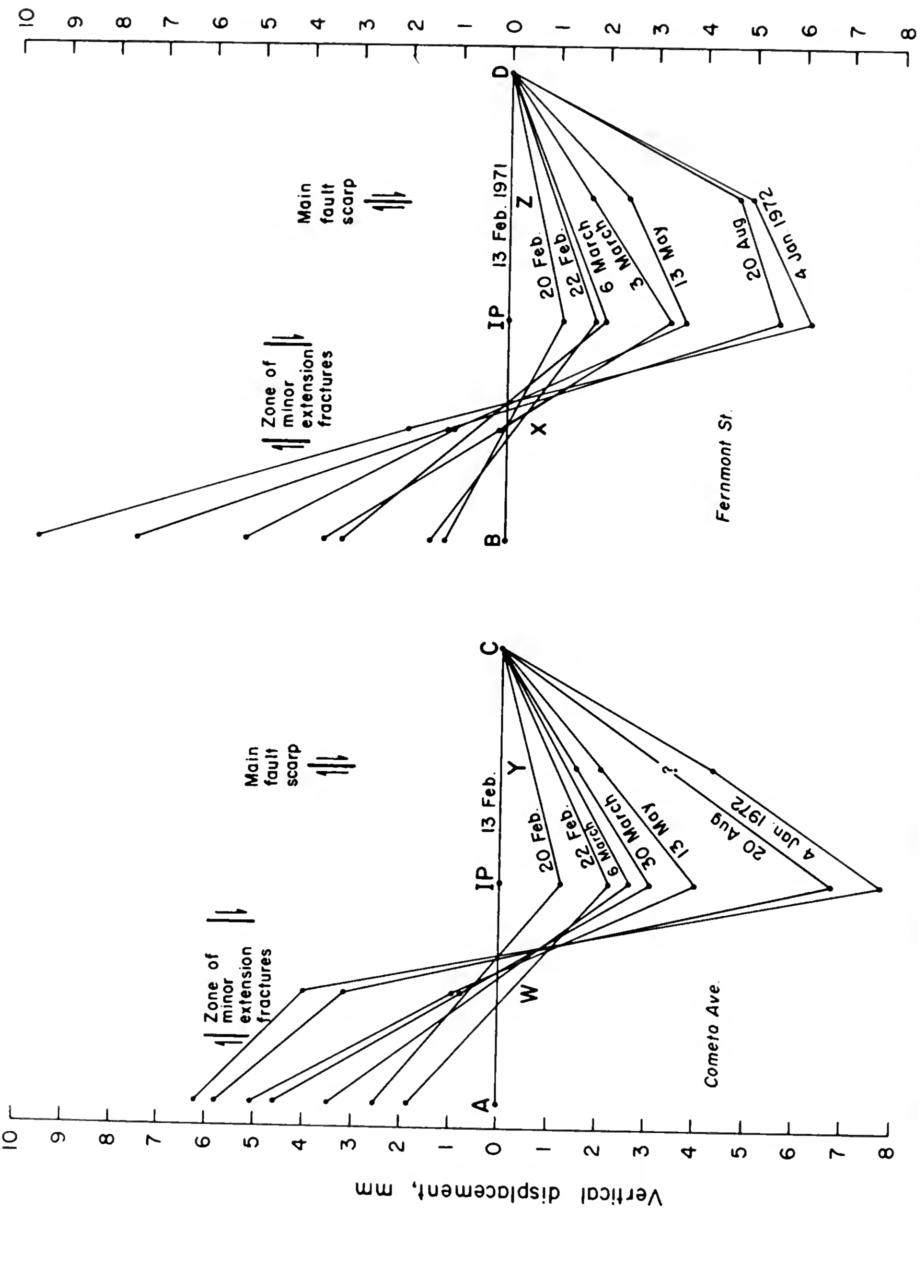


Figure 2. Comparison of repeat measurements with initial set. C and D are arbitrarily fixed to show relative elevation changes of points across the fault.

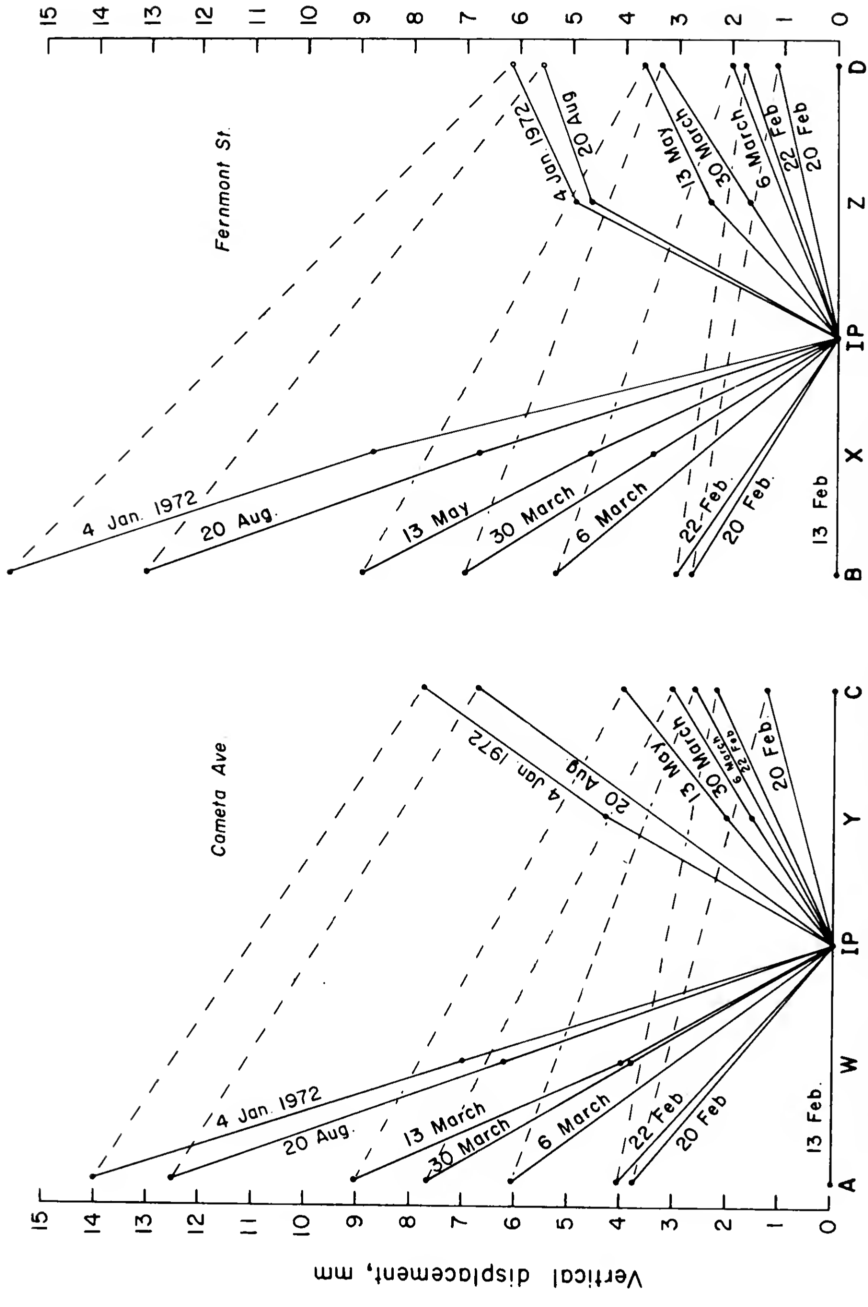


Figure 3. Comparison of repeat measurements with initial set. Point IP is arbitrarily fixed to show relative elevation changes of the endpoints of the lines. Elevations for point D (open circles) are calculated from auxiliary monuments as explained in the text.

to any of the points was a hairline extension fracture 4 m southeast of A (figure 1). No cracks were observed in the streets beyond the projections of our lines. Point D (figure 1) was finally obliterated by street repair crews prior to the resurvey of August 20, but its probable elevation in subsequent resurveys has been calculated from elevations of surrounding auxiliary monuments. A trench, 1 m deep, was dug within half a meter of IP sometime around March 1 and filled shortly thereafter. The elevation of IP changed anomalously with respect to the endpoints, but the change also occurred before the excavation and thus is probably not attributed to settling of the ground around the trench, as is discussed in the next section. Angles were turned to each endpoint with a shaded Wild T-2 theodolite at IP. Street repair crews and heavy sightseeing traffic during the first two weeks precluded safe and accurate taping of distances, so distances from IP to the endpoints were measured with the T-2 and a Wild subtense bar. The mean precision of the angles for all surveys is ±1 second, but the error associated with the distances is ± 2 cm which exceeds horizontal component of afterslip we would expect from our leveling data by an order of magnitude.

Each leg of the X-figure was leveled independently, the only point in common being IP. All leveling was double-run with balanced sights of approximately 25 m using a shaded Wild N-3 tilting level with two Wild invar leveling rods. The leveling was usually done in the morning or late afternoon when heat refraction effects were slight or not present. Closing errors of each leg of each survey were less than 0.3 mm. The estimated average error for any given point, as obtained by comparison of our repeated levelings on different dates in stable areas elsewhere, is ±0.2 mm.

The initial leveling was done on 13 February, four days after the main shock. Observations were repeated on 20 and 22 February, 6 and 30 March, 13 May, 20 August 1971, and 4 January 1972. Monuments W, X, Y, Z (figure 1) were established and leveled on March 6 to get a better idea where the slip was taking place.

RESULTS

The seven relevelings show minor cumulative differences among the elevations of the five points. The magnitude and consistency of the displacements are consistent with afterslip measurements across surface ruptures elsewhere in the meisoseismal area (Burford and others, 1971; Lahr and others, 1971; Nason, 1971; Savage and others, 1972). The elevation differences of each set of repeat measurements are compared with the initial set in figures 2 and 3. In figure 2, C and D are arbitrarily fixed to show the relative elevation changes of A, B, and IP across the fault. In figure 3, the common point of the two lines, IP, is arbitrarily fixed to show the relative elevation changes of endpoints of the lines. It is clear that A and B have risen consistently relative to C and D and that IP has dropped relative to the four endpoints.

The cumulative displacements of A and B relative to C and D are plotted in figures 4 and 5 which show that nearly half of the displacement occurred within 10 days of the first leveling. The rate decreased logarithmically to about 1 mm per 100 days after May 13. This corresponds to the general decline in the frequency of the aftershocks (Espinosa and others, 1971).

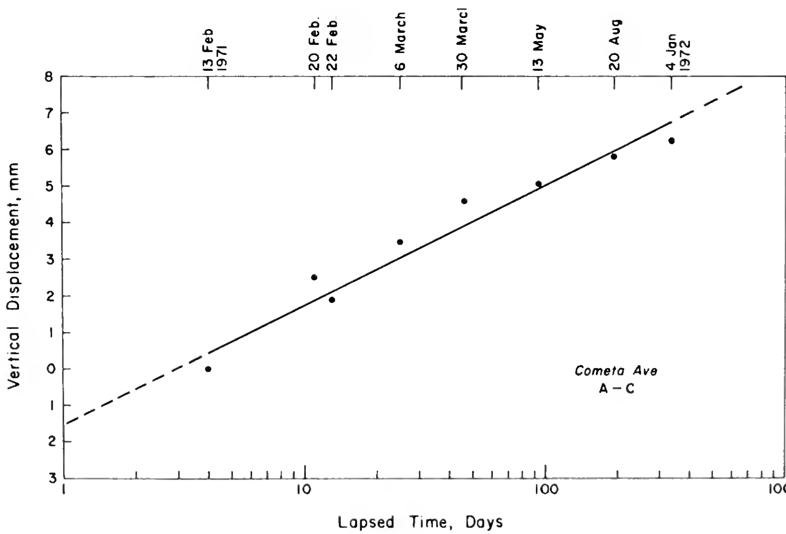


Figure 4. Cumulative vertical displacement vs. log time of point A with respect to point C.

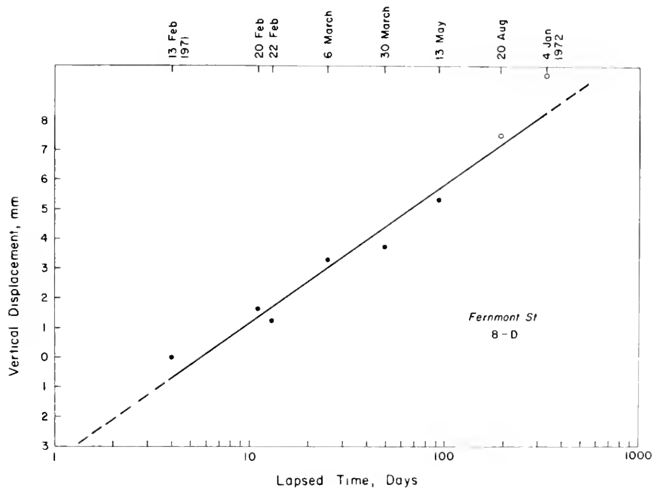


Figure 5. Cumulative vertical displacement vs. log time of point B with respect to point D. The elevation differences for the surveys of 20 August and 4 January (open circles) are approximate, because the elevation of D had to be calculated from elevations of surrounding auxiliary monuments.

The magnitude of the displacements, however, is small compared to the initial vertical component of slip of 75 cm at this locality determined by Kamb and others (1971) and by the U.S.G.S. (1971). Indeed, the rather even and minor displacements we measured may be attributed merely to gradual dehydration of the ground from winter to summer. However, inasmuch as the greatest elevation change occurred within a few days of, and is consistent in direction with the main initial displacement (north block up relative to the south block, figure 1), we consider the data show evidence of real, but minor, afterslip on this portion of the fault.

The anomalous, but consistent, drop of IP relative to the endpoints may be due to one of the following mechanisms:

1. compaction of the ground which was dilated by fracturing near the fault scarp;
2. southward tilting of the south edge of the north block about an axis parallel to, and north of, the fault scarp; and
3. slight near-surface lateral-spreading of the ground and/or of a major slab of the asphalt street downhill (south) toward the free face of the scarp.

Longer level lines and more data points would be required to make a clear choice among the possibilities; however, the third mechanism is supported by the triangulation data which show that the angle C-IP-D consistently increased by an amount about equal to the sum of the changes of the other three angles, all of which decreased. Angle A-IP-B should not have changed unless movement occurred on a minor fracture north of IP. We cannot rule out this possibility, but further speculation about the behavior of a single data point does not seem warranted.

DISCUSSION

This study and others (Lahr and others, 1971; Nason, 1971; Burford and others, 1971: Savage and others, 1972) show that afterslip accounts for less than 2 percent of the total slip from 1½ to 330 days following the main shock of the San Fernando earthquake. This is of particular interest in view of the relatively large contribution of afterslip to the total slip in the recent California earthquakes of comparable magnitudes at Parkfield and Borrego. The evidence from both earthquakes suggested that afterslip may be the result of the delay in propagation of slip from relatively rigid basement rocks through the overlying relative nonrigid sedimentary rocks (Smith and Wyss, 1968; Scholz and others, 1969; Burford, in press).

Approximately 3–4 km of sedimentary rocks overlie the crystalline basement in the Sylmar area, based on a gravity-density model of the San Fernando Valley (Corbató, 1963). The upper part of the sedimentary sequence is composed of as much as 1,800 m of partially indurated sand and gravel of the Plio-Pleistocene Saugus Formation which closely resembles the relatively thin veneer of overlying unconsolidated alluvium

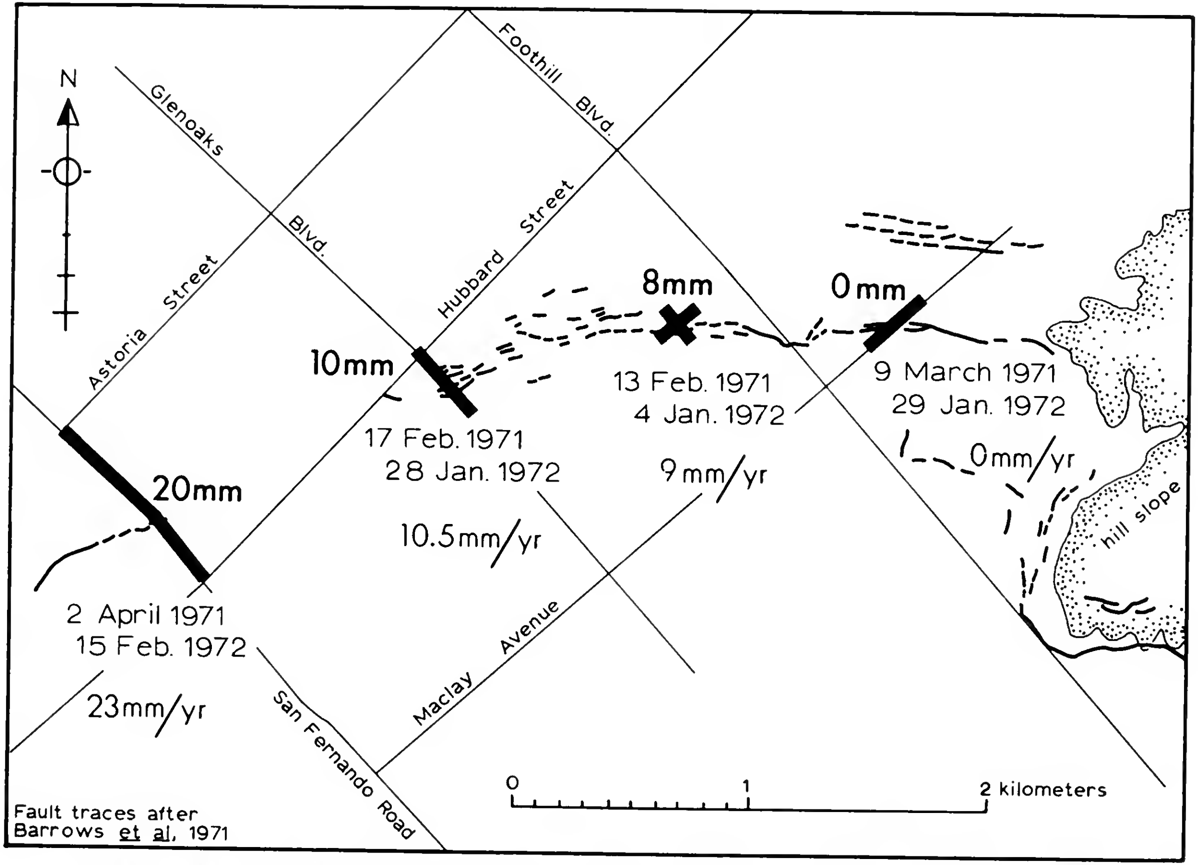


Figure 6. Relative elevation changes across parts of the Sylmar and Mission Wells fault segments. Heavy lines are releveled segments of longer initial levelings done shortly after the earthquake. The X-figure is discussed in this report. Data include observed elevation differences in millimeters and dates of initial and repeat levelings. The observed elevation changes are normalized to millimeters per year to show the variation with respect to observation intervals.

(Wentworth and Yerkes, 1971). Thus the sedimentary blanket is apparently comparable in thickness and lithologic character to those at Parkfield and Borrego Mountain; but the absence of significant afterslip at Sylmar does not support the slip propagation delay mechanism outlined above, unless basement is much shallower beneath the surface ruptures than Corbató's model suggests.

The afterslip phenomenon may be related in a more fundamental way to the mechanism and relative efficiency of release of stored elastic strain throughout the entire rupture volume rather than just within the near surface portion of it (Nason, 1969). Experimental studies of rock deformation (Byerlee and Brace, 1968) have shown that rock failure at low pressure occurs in most rock types by abrupt faulting with low stress drops followed by stable sliding which is analogous to afterslip. At high pressures and low temperature, however, faulting occurs only by sudden, violent stick slip with relatively large stress drops; no movement follows the initial faulting because the stored elastic strain energy is almost completely released in the single "main shock."

Extension of these experimental results to earthquakes suggests that, when the stress reaches a critical value for slip on a segment of a fault between two strongly compressed crustal blocks, violent and sudden faulting will take place along the entire segment (Byerlee and Brace, 1968). Thus, available stored elastic strain would be released abruptly and almost completely throughout the entire rupture volume, and further movement, including afterslip, would be precluded until the slow process of stress build-up and strain accumulation again reach the critical value for violent and sudden release. The hypothesis suggests that this process should be expected with earthquakes on "compressional" type faults which concentrate relatively high stresses. In California, these would include bent sections of major strike-slip faults (Wyss and Brune, 1971) as well as high-angle reverse faults and thrust faults like the complex Sierra Madre fault system along part of which the 1971 San Fernando earthquake occurred.

Clearly, many more detailed geodetic studies are needed along all of California's major faults, not only to document the mechanism of strain release after earthquakes, but also to document the mechanism of strain accumulation before earthquakes.

AS WE GO TO PRESS

Short segments of first-order lines, leveled initially by other surveyors shortly after the earthquake, were releveled early in 1972 to determine the variation in afterslip along the length of the Sylmar fault segment. The results are summarized in figure 6 which shows that afterslip is small or absent on the east end of the Sylmar segment where the maximum uplift occurred and is larger, though still negligible, on the western end of the Sylmar segment and on the Mission Wells segment where initial uplift was less than 0.5 m. The elevation changes occur where the level lines cross the principal displacement zone and are not functions of the length of the repeated line as is suggested by the figure. The elevation changes are normalized to a rate in millimeters per year merely to show the variation along the fault with respect to the interval of lapsed time.

Observed elevation data for initial levelings were generously provided to us by VTN Engineers of Van Nuys and by the Survey Division under the supervision of the City Engineer of the City of Los Angeles.

ACKNOWLEDGMENTS

We are indebted to the many University of California at Santa Barbara students, relatives, neighbors, and Sylmar residents who assisted us in the surveying. The U.S. Geological Survey, through R. O. Burford, lent us some of the necessary equipment and offered much valuable advice. R. O. Burford, J. C. Savage, and W. T. Kinoshita are thanked for the use of their manuscripts before publication. The manuscript benefitted from the suggestions of R. O. Burford, R. D. Nason, and J. C. Savage. The study was partially supported by the Sea Grant Program of the National Science Foundation under grant GH 95.

CHAPTER 19

Effects of the Earthquake on Residential Areas[1]

by James E. Slosson [2]

The violent earthquake that shook the general Los Angeles area on February 9, 1971, brought havoc and devastation to the northern portion of the San Fernando Valley and the San Fernando Pass area. The extent of damage decreased radially away from the center of destruction. Damage was noticeable more than 30 miles from the epicenter. The earthquake had a magnitude of 6.5. Its epicenter was located in a remote portion of the San Gabriel Mountains approximately 3 miles south of the Antelope Valley Freeway (Interstate 14). Zones of surface rupture associated with faulting were within the general San Fernando-Sylmar area, approximately 9 miles south of the epicenter. The zones of rupture correspond with the area of maximum energy release. The fault motion or displacement was associated with a relatively steep, high-angle reverse fault that dips steeply from the surface rupture zone in San Fernando-Sylmar to a depth of 7 to 8 miles below the epicentral area. Thus a block or portion of the San Gabriel Mountains was thrust upward toward the south, or toward the San Fernando Valley. Associated with the main thrust motion was a lateral component (left-lateral motion) that was lesser but still significant.

The February 9 earthquake occurred at approximately 6:00 a.m., a time when most people were still at home. Considering the damage to the freeway system in the San Fernando-Sylmar area and to the public and commercial buildings in the west-central portion of Los Angeles along with the crowded condition that generally prevails on the streets and sidewalks of Los Angeles, both the fatalities and injuries would have been much higher if the earthquake had occurred even an hour later.

In retrospect, the inhabitants of the areas most severely damaged were lucky that they were at home when the temblor struck. The typical one-story, single-family dwelling withstood the great forces of energy released by the earthquake remarkably well. Some single-family dwellings were damaged and some were destroyed, but there were only two fatalities as compared to 56 fatalities associated with other types of structures. This fact is even more remarkable when it is considered that over 90 percent of the people within the area of the earthquake were in residential structures at 6:00 a.m. on February 9.

The residential areas that received the greatest amount of damage were the city of San Fernando, where approximately 30 percent of the residential structures sustained appreciable damage, and the city of Los Angeles, where severe damage occurred in the suburb of Sylmar. Also within the city of Los Angeles, there was lesser, but still important, damage in the suburbs of Granada Hills, Sunland-Tujunga, and Pacoima. Regions within Los Angeles County which were damaged included the Kagel Canyon-Little Tujunga Canyon area and the Saugus-Newhall area.

Plate 3 illustrates graphically the areas of major destruction as related to the zones of faulting and other entities of the geological environment.

PRINCIPAL ZONE OF DAMAGE

City of San Fernando

San Fernando, a small incorporated area in Los Angeles County, incurred the highest per capita percentage of damage to residential structures. San Fernando is 2.4 square miles in size and maintained 5210 living units at the time of the 1970 census. A detailed study performed by the City of San Fernando after the earthquake listed 165 single-family dwellings as demolished, 100 empty residential buildings needing rehabilitation, and 150 with major damage (over $7500 per unit). Also listed were 26 apartment living units demolished and 75 damaged and in need of major repair. In all, approximately 1500 of 5210 units sustained appreciable damage. Originally, 270 units were tagged as unsafe, but this number was eventually increased to 300. The statistics eventually indicated that an estimated 30 percent of the residential units were appreciably damaged with the total for these losses calculated at $12,125,000. It is further estimated that 30 to 35 percent of all of structures in San Fernando were damaged.

The area in San Fernando that had the highest residential damage was the pre-1933 section of town. However, the most concentrated damage occurred in a zone where extensive ground rupture inferred to be associated with faulting took place.

City of Los Angeles

Within Los Angeles, the heaviest damage occurred in that area closest to the zone of surface expression or surface rupture associated with the earthquake. This

[1] Manuscript submitted for publication December 8, 1971.

[2] Los Angeles Valley College at time of earthquake; now California Division of Mines and Geology, Sacramento.

Figure 1. Location of vacated structures in the City of Los Angeles. See also plate 3.

Single-family dwellings	
Demolished	165
Empty—need rehabilitation	100
Major damage (over $7,500.00)	150
Minor damage	1000±
Total	1415±
Apartment buildings	
Demolished	26
Damaged	75
Total	101

area was the northern portion of the San Fernando Valley. Approximately 500 residential units were vacated in Los Angeles, with over 90 percent of the vacated structures being adjacent to, or in the immediate vicinity of, the surface expression of the fault motion. The unsafe or severely damaged apartments, however, showed a different statistical and geographical pattern, with the greatest number (greater than 80 percent) being located within the general downtown Los Angeles area some 20 or more miles from the area of greatest residential damage.

Figure 1 depicts the location of vacated structures within the city of Los Angeles. It clearly shows the greatest damage to residential structures to be in the Granada Hills, Sylmar, and Sunland-Tujunga areas and the greatest damage to apartment buildings to be in the Central Los Angeles area.

The higher loss in apartment buildings for Los Angeles is almost directly associated with time of construction. The pre-1933 structures had a much higher loss factor than the modern structures.

Table 2. Estimates of monetary loss in Los Angeles attributed to the earthquake.

	Number	*Monetary loss*
Unsafe but possibly repairable		
Single-family dwellings	501	$12,500,000±
Apartment buildings	59	11,500,000±
Major structural damage		
Single-family dwellings	2,469	$24,500,000±
Apartment buildings	192	7,500,000±
Minor damage		
Single-family dwellings	13,711	$7,500,000±
Apartment buildings	1,748	17,500,000±
Total single-family dwellings	16,781	$44,000,000±
Total apartment buildings	1,999	$36,500,000±

County of Los Angeles

The heaviest damage in the area covered by the jurisdiction of Los Angeles County was in the Kagel Canyon-Little Tujunga Canyon area and Saugus-Newhall area with lesser damage in the La Crescenta Valley and outlying areas. In general, the greatest damage was sustained by older structures, and the greatest number of damaged structures were close to the epicenter or the zones of surface rupturing. Within these areas of damage, 64 single-family dwellings and seven apartment structures were posted unsafe. Statistics show that chimneys were damaged or failed in less than 30 percent of those structures sustaining damage and that less than 20 percent showed wall damage.

	Number	*Monetary loss*
Buildings posted unsafe		
Single-family dwellings	64	$438,500
Apartment buildings	7	77,500
Buildings damaged		
Single-family dwellings	2,141	$1,282,290
Apartment buildings	62	96,825
Total single-family dwellings	2,205	$1,720,790
Total apartment buildings	69	$174,325

The total of the statistics from the City of San Fernando, City of Los Angeles, and County of Los Angeles indicates that approximately 19,771 single-family dwellings were damaged and 730 were demolished or required major rehabilitation. Ninety-two apartment buildings were demolished or required major rehabilitation, and 2,077 apartment buildings were damaged.* The total estimated monetary loss associated with these affected structures is $97 million, of which $58 million loss was to single-family dwellings.

Population within the areas of strong to very strong ground shaking (.20g to .50g) under the jurisdiction of the City of Los Angeles exceeds one million; out of this population, there was one recorded fatality within a residential structure. Therefore, the casualty factor for occupants of the residential structures in the northeast part of Los Angeles was less than 1 person per 1,000,000. In addition, the statistics for residential structures within the entire area affected by strong to very strong ground shaking indicate that there were two fatalities (including the one listed for the City of Los Angeles) in a region with a population of approximately 2,500,000. This region includes the affected City of Los Angeles and the unincorporated portions of Los Angeles County such as Saugus-Newhall and the foothills bounding San Fernando (population less than 1,000,000). Thus the casualty factor for residential structures within the entire area affected by strong to very strong ground shaking was somewhat less than 1 person per 1,000,000.

Considering that approximately 90 percent of the people in these areas were in their residences at the time of the earthquake, the casualty factor for the February 9, 1971, earthquake was phenomenally low, averaging approximately one in one million.**

The damage factor within a given area was generally high for older, masonry types of residences. The modern homes, with some exceptions, performed quite well. Some of the damage was associated with consolidation and settlement of fills in tracts for single lots developed prior to 1963 when the modern grading codes were introduced. Many of the severely damaged

* Also damaged in Los Angeles County were 1,707 mobile homes for which no monetary loss factor has been determined.

** NOTE: The building regulations are more rigid and more strictly enforced in Los Angeles than in other cities in California.

structures were located upon fill material where the sites were graded prior to the early 1950s (no grading regulations prior to 1952). The largest number of seriously damaged or destroyed homes were located on alluvial deposits; and, in turn, the greatest damage was associated with the less consolidated alluvium.

DAMAGE RELATED TO THE GEOLOGIC ENVIRONMENT

Surface Rupture Associated With Faulting

One of the most heavily damaged zones was the area within San Fernando together with a portion of Sylmar that extends from near the intersection of Foothill Boulevard and Maclay Avenue to and through the intersection of Glenoaks Boulevard and Hubbard Street. This rupture zone extended west and east through less populated areas where, for this reason, less destruction occurred. Within this zone, which averaged a few hundred feet in width, almost every structure, both housing and commercial, was either damaged or destroyed. See photos 1, 2, 3, 4, 5, 6, 7.

This zone of surface rupturing appears to be closely related to a fault zone that had been considered inactive and was only subtly suggested by topography but was more clearly delineated by presence of a groundwater barrier. The most recent pre-February-9 activity appears, from available data, to have occurred thousands or even tens of thousands of years ago.

Other less extensive zones of rupture were noted in the Kagel Canyon and Little Tujunga area of the City of Los Angeles. Few structures were over or immediately adjacent to rupture zones due to the more remote, hilly nature of the terrain, so that far less damage due to fault-induced ground rupture occurred. Some commercial structures were affected, and almost all of the utilities were ruptured and made temporarily inoperative.

Fault offset was measurable in the residential tract at the northerly terminus of Hubbard Street in the suburb of Sylmar. In this zone, the vertical fault offset was 6 inches to 30 inches and typified the high-angle reverse fault pattern of the February 9 earthquake. The tract directly affected was in various stages of construction, ranging from occupied homes to structures in the framing stage. All were greatly affected. See photos 8, 9, 10, 11, 12 and figure 2.

Surface Rupture Associated With Lurching

Many housing areas overlying alluvial materials and/or pre-1936 fill materials were subjected to intense shaking and resulting ground rupture. The ruptures generally ranged from small to hairline cracks. Often these cracks continued into the footings and structural portions of the residential units. Photo 13 was taken

Photo 1. Example of damage incurred by residential structures in zone of ground rupture and intense shaking. Failure of garage was primarily a result of horizontal motion. *Photo courtesy of City of Los Angeles Department of Building and Safety.*

Photo 2. Damage resulting from both horizontal and vertical motion. Structure moved laterally, partially off of its footing. *Photo courtesy of City of Los Angeles Department of Building and Safety.*

Photo 3. One of the many chimneys that collapsed. In this house, support for porch also fell. *Photo courtesy of City of Los Angeles Department of Building and Safety.*

Photo 4. This apartment building, on Foothill Boulevard near Maclay Avenue, was damaged by both vertical (21"±) and horizontal (12"±) motion. Carport type of garage under second story dwelling is very susceptible to earthquake damage. *Photo courtesy of City of Los Angeles Department of Building and Safety.*

to show the general pattern and magnitude of these cracks. Photos 14, 15, 16, and 17 were taken in the vicinity between Olive View Hospital and the Veterans Administration Hospital. This cracking in this zone appears to be the result of its geologic location. The uplifted bedrock mass of the San Gabriel Mountains is immediately to the north and bounds the alluvial apron upon which the housing area shown in these photos and Olive View Hospital are located. The inferred effect is one of high velocity earthquake waves being transmitted through the bedrock into alluvial material which slowed the velocity and converted the waves into waves of lower velocity and higher amplitude—thus creating slower, longer shaking conducive to the production of lurch cracks.

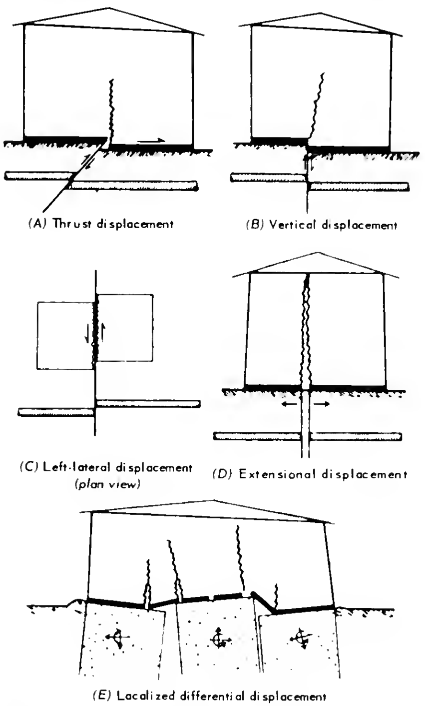


Figure 2. Sketches showing the type of damage associated with ground damage. *(Figure 6 from U.S. Geological Survey Bulletin 733)*

A similar zone of lurch cracks bounds the zone of fault-induced rupture between Foothill Boulevard and Hubbard Street. Apparently, when fault rupture occurs in an area mantled by alluvium, many of the ruptures extend to the surface. In addition, the energy released in the ruptured zone resulted in intensive shaking which, in turn, created lurch cracks.

Ground cracks induced by lurching are also noticeable in areas of man-made fill extending from Big Tujunga Canyon to the Knollwood area of Granada Hills and in various locations within the Saugus-Newhall region (see photo 18). The extent and degree of rupturing appears to be associated with the method of placing these fills. As an example, fills at Camp Karl Holten in Little Tujunga Canyon were severely damaged (see photo 19) as compared to no noticeable damage at the Hathaway School, also in Little Tujunga Canyon (see photo 20).

There are three main factors to consider when evaluating the degree of rupturing associated with man-made fills. One, of course, is the proximity of the fault rupture or location of maximum energy release; the second is the type of material (solid bedrock, alluvium, water-saturated alluvium, etc.) on which the fill is placed; and the third, and most important, is the method of fill placement and the supervision or quality control factor.

Damage Resulting From Intense Shaking

Generally there was a direct correlation between the amount of structural damage and the proximity of the location of maximum energy release and/or the surface expression of the fault. Giving consideration to the type of structure, the era of construction, and the degree of control by both governmental agencies and the contractor (quality control) there is still a greater damage factor associated with the nearness of the energy release. Thus the San Fernando-Sylmar area was most severely damaged, and the areas further away were less damaged.

Settlement and Other Related Fill Failures

Settlement of fill materials was noted from the La Crescenta Valley to the Granada Hills area in the fault zone and in the Saugus-Newhall area near the epicenter. Generally, there was a very noticeable relationship between the number and degree of failures and the time the fill was placed. In areas such as Kagel Canyon, where almost all of the fill was placed prior to the initiation of grading codes, failure was nearly universal. In areas where the fill was placed as an engineered fill, but prior to the modern, effective grading codes which were developed by the City of Los Angeles in 1963 and more recently followed by Los Angeles County, the failures were less extensive. Few, if any, failures occurred in areas graded since the development of the modern codes. This strongly suggests that good engineering practices and quality control supervision should be mandatory in areas subject to earthquake activity.

DAMAGE RELATED TO TYPES AND VINTAGE OF STRUCTURES

In general, pre-1933 residential structures sustained greater damage than modern structures. The greatest damage appeared to be associated with stone and other masonry residential structures, especially in San Fernando (see photos 3 and 21). Damage to multi-story apartment houses shows a strong relationship to vintage, as is indicated by figure 1 which shows the greatest number of vacated apartment buildings to be located in the pre-1933 section of Los Angeles (Hollywood and central Los Angeles).

Photo 5. Boys Market, at the corner of Glenoaks Boulevard and Hubbard Street, collapsed as a result of ground displacement and ground lurching in combination with intense shaking. *Photo courtesy of Robert E. Wallace, U.S. Geological Survey.*

The wood-frame and stucco, one- and two-story residential structures survived the earthquake relatively well. Some of the modern, split-level, two-story residential structures with the second floor over the garage proved to be very susceptible to earthquake failure (see photos 15 and 22). The failure of this type of structure was related to one or more factors. The first and most important of these factors was the lack of structural wall support for wall area occupied by the garage door; steel bracing in the garage door area was shown on the approved plans but was never placed. A second factor was related to the often inadequate structural tie btewcen the two-story portion and the single-story portion. A third weakness was the bracing of the cripple walls of the one-story portion which failed, allowing this portion to settle, thus removing support and allowing or causing failure of the two-story portion (see photos 23 and 24).

The following are items that were noted as typical failures associated with single-family dwellings and apartment buildings.

A. *Chimney anchorage:* Pull-out strips; nails pulled out; and wood-tie failure occurred; chimney fell (see photo 25).

B. *Veneer anchorage in dwelling:* Large pieces of veneer spalled off.

C. *Bracing in exterior walls and cripple walls of dwellings:* Failures of walls indicated inadequate bracing (see photo 26).

D. *Cutting, notching, and boring of wood studs:* Splitting or failure of wood studs indicated excessive cutting, notching, and boring of studs.

E. *Tile and cement shingle roof attachments:* Considerable shifting of tile and cement shingles.

F. *Ties between different levels of wood frame construction and individual components, particularly in split-level construction and individual components:* Numerous structural failures occurred between different levels of wood frame construction; large header beams pulled away from seats.

G. *Anchorage of water heaters:* Many water heaters fell over in the earthquake; apparently this was usually the result of the utilization of flexible tie connections.

H. *Stapled anchorage of gypsum board and wallboard in shear walls:* Staples did not appear to hold as well as normal nail construction; extensive cracking at gypsum joints was evident; improper adjustment of mechanical stapling machines may have been a major factor.

I. *Mechanical application of nails:* The pulled-out diaphragms from exterior ledges indicates a study should be made of

Photo 6. The commercial area at the southwest corner of Glenoaks Boulevard and Hubbard Street was damaged by displacement, lurching, and strong ground motion. *Photo courtesy of Robert E. Wallace, U. S. Geological Survey.*

adjustment of the mechanical nailing equipment, the methods of nailing, and the type of nails used.

J. *Ancharage of non-bearing partitions:* Many non-bearing partitions were dislodged.

K. *Ancharage of lighting fixtures:* Many lighting fixtures fell during the earthquake.

L. *Accessibility of utility shutoff devices:* The movement of water heaters and forced air furnaces created a fire hazard due to dislocated gas lines and vents; the failure of ceiling light fixtures and the dislodging or failure of walls affected electrical systems and presented a fire hazard.

Photo 7. Example of street damage that affected travel to and from residential areas.

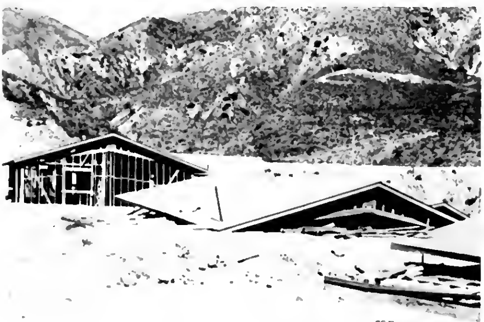


Photo 8. The structures in the foreground were framed only, with no lateral support. The structure in the background had part of the wire mesh placed in preparation for plastering; this difference in lateral support gave greater strength to the partly built structure, which survived better. Rojah Street and Wallabi Avenue area. *Photo courtesy of the City of Los Angeles Department of Building and Safety.*

HAZARDOUS EXTERNAL CONDITIONS

Water Supply

The near-failure of the San Fernando Dam clearly indicated the hazard posed by the presence of housing areas in the proximity of a non-modern dam and reservoir. Lower San Fernando Dam was located within 2 miles of the zone of fault rupture and on strike with it and high energy release. It is assumed the equivalent peak lateral acceleration in the vicinity of the dam was between 0.4g and 0.5g. The force and intensity of the shaking caused a failure on the upstream side of the dam. This reduced the freeboard to a few feet and placed the dam and some 80,000 people immediately downstream in danger for approximately 48 hours. A zone between the San Diego Freeway and Balboa Boulevard extending from the downstream face of the dam near Rinaldi Street to the Los Angeles River Channel some 7 miles away was evacuated until the water level was reduced in the reservoir and the hazard passed (see paper by Cortright in this bulletin).

Modern dams constructed with modern equipment, current engineering techniques, and, above all, adequate knowledge of the geologic environment should not present a similar hazard. Lower San Fernando Dam was completed first in 1915 utilizing conventional hydraulic fill. Upper San Fernando Dam, completed by the semi-hydraulic fill method in 1921, also sustained damage. A new smaller dam within the Van Norman Reservoir Complex survived the earthquake without damage. The concrete-arch Pacoima Dam sustained no significant damage in spite of high ground acceleration.

Several large water storage tanks were damaged. The most spectacular damage was to the tank at Olive View Hospital which developed a wrinkle at the base and ruptured as shown in photo 27. Others included the large Los Angeles Department of Water and Power Sesnon Tank in the Porter Ranch area and a Metropolitan Water District tank near the Jensen Filtration Plant. Almost all of the storage tanks in the Sylmar-San Fernando area were toppled, ruptured, or had their attachment lines severed.

The water system for the City of San Fernando was devastated. The sole supply from a once intricate system of wells and tanks was one well in the northern section of town. Wells were ruptured; reservoirs were cracked (two beyond repair); and the distribution system was so fractured that it had to be almost entirely rebuilt.

Among the hazards associated with urban development in areas subject to earthquakes are the damaging effect on the supply system and the hazards presented by older reservoirs. Many households in the Sylmar-San Fernando area were without City water for 1 week to 4 weeks.

Other Utilities

Natural gas lines within the Sylmar-San Fernando area were ruptured, creating a danger. Had these failures occurred during working hours when traffic would have been heavier, the danger of fires would also have been much greater. These failures also left many people without gas for cooking and heating for many weeks.

Electrical lines were severed, creating a fire danger and a potential for electrocution. The electrical systems within the main area of devastation were nonfunctional for periods up to a week. Some fires attributed to electrical failures did occur, and a few

Photo 9. Partially completed structure with a good portion of sheathing and wire mesh placed. Rajah Street and Tucker Avenue area. *Photo courtesy of the City of Los Angeles Department of Building and Safety.*

homes were lost due to fire. Another difficulty associated with this type of fire is the inability to contact the fire department following an earthquake because of telephone malfunction.

Other utilities that were damaged, directly affecting the residential areas of Sylmar-San Fernando and some of the immediately adjacent areas, were: Sewer lines, which became inoperative, creating potential groundwater pollution; Streets, impeding and halting traffic; storm drains; telephone facilities, damaged by severed lines and devastated plants; reduction in hospital and other emergency facilities' availability; and partial loss of communication with emergency equipment. Good communications during and after an earthquake are imperative, and a workable emergency information plan must be prepared before the next earthquake occurs.

In conclusion, damage to public facilities greatly endangered and inconvenienced the inhabitants of the residential areas and demonstrated the total reliance on these systems by people living in modern urban areas.

CODE CHANGES AND CONSTRUCTION TECHNIQUE REVISIONS

As a result of the February 9, 1971, earthquake, many jurisdictions and governmental entities have changed or are changing codes and regulations regarding earthquake hazards. Almost all should be beneficial; some appear to be nonfunctional and confusing; and one possible change appears to be a step backward. Probably the most realistic and beneficial are the changes that the City of Los Angeles has made in its building codes and requirements for the design of structures in urban areas subject to earthquake activity.

The changes in building codes for the City of Los Angeles will provide greater safety and hopefully will eliminate many, if not almost all, of the problems that led to damage in the February 9 earthquake. The increase in cost for a typical single-family dwelling or apartment building should be minimal. Estimates indicate that the increase should be less than 1 percent of the total construction cost. The majority of the changes in the code are those requiring closer supervision and quality control of work performed.

It is feared by some community leaders that high standards and strict enforcement may drive away the building industry, but public safety suffers wherever this philosophy prevails. Some feel that the need to reestablish the economy promptly must be given prime consideration, and thus some local governments tend to reduce standards rather than require the high standards essential to prevent repetition of the same errors and damage.

Some of the obvious and necessary changes that the City of Los Angeles has made in their building requirements are listed in the Appendix to this report.

The City and County of Los Angeles, and hopefully other jurisdictions, will require detailed founda-

Photo 10. Portions of structures lacking adequate lateral strength sustained greater damage than those with adequate strength. *Photo courtesy of the City of Los Angeles Department of Building and Safety.*

Photo 11. Newly completed structure with repairable damage. Here lateral support was sufficient to prevent collapse. Nevertheless, the chimney fell, windows shattered, and some walls were damaged. *Photo courtesy of the City of Los Angeles Department of Building and Safety.*

Photo 12. Houses being framed (photo 8) were located in top center; those partially completed in the left center and top left (photo 9); and those completed are in the foreground and far right (photos 10 and 11).

Photo 13. Ground cracks resulting from lurching. *Courtesy of H. G. Andersan, Los Angeles Valley College.*

tion engineering, seismic engineering, and engineering geology reports for all major structures. In addition, similar detailed data will become a requirement for urban development within areas subject to earthquake hazards located in the City and County of Los Angeles. Hopefully, to prevent and/or minimize the damage and loss of life wrought by the earthquake, which is one of the greatest of the geologic hazards, other jurisdictions and governmental entities will require similar technical data.

A report of the "Task Force on Earthquake Hazard Reduction, May 4, 1970" issued by the Institute of Governmental Studies at the University of California, Berkeley, suggested:

"*Urban Planning for Seismic Safety*

All plans and land use controls at every level—federal, state, regional, and local—should have earthquake-anticipation components suited to prevailing seismic and soil conditions.

1. Urban areas near geologically young or active earthquake faults, and those farther away that are likely to experience significant earthquake shaking, should be zoned for building purposes. Construction in such zones should be subject to regulations by governmental agencies that are capable of administering and enforcing them on fair and equitable bases. These controls should be designed to minimize future casualties and property damage, so far as is economically feasible. The regulations should be related to the proximity of faults, the likelihood of major earthquakes, estimates of their probable maximum magnitude, soil and water-table conditions, hills and other natural features, population concentrations, and the degree to which known hazards can be minimized by raising design standards.

2. As the state governments expand their roles in earthquake-hazards reduction, they will need to include earthquake anticipation components in all planning for state-supported facilities, and to require appropriate earthquake-anticipation components in the plans of all subsidiary local governments.

Information Before, During and After Earthquakes

1. Data on ground movement should be obtained before, during and after major earthquakes. Special efforts must be

Photo 14. Two-story, split-level, residential structure (Almetz Street) which sustained damage due to insufficient lateral support provided by ground garage opening and collapse of cripple supports under single-story portion. *Courtesy of the City of Los Angeles Department of Building and Safety.*

devoted to the placement of additional strong-motion seismic equipment. This is essential for the collection of information needed to develop improved structural designs for earthquake resistance. Because of their crucial nature, strong-motion data on destructive earthquakes anywhere in the world should be obtained, whenever possible.

2. Better maps of several kinds are required, including more definitive seismicity or earthquake probability maps; more detailed [maps of] earthquake geologic hazards of metropolitan areas; more informative maps of faults (including displacement histories, especially over the past two million years); and improved maps of deposits at or near the surface.

3. The earthquake safety of older structures should be reappraised, as should that of old and new facilities when new hazards are discovered.

4. Public officials, the public and disaster relief agencies such as the Red Cross, should be appropriately and systematically involved in planning how best to prepare for an earthquake. They should be thoroughly briefed on what to do during and after an earthquake. State and local governments need information on the protective and recovery measures that can be taken.

5. During and after an earthquake, good communications will be essential among responsible federal, state, and local officials, and voluntary relief agencies such as the Red Cross. If this goal is to be achieved, a centralized emergency information facility—and a workable emergency information plan—must be in existence before the earthquake occurs."

The California Legislature has considered a number of bills related to earthquake studies, safety, and insurance. Possibly the most beneficial measure to the home owner, if passed, would be one which requires that engineering geology reports be submitted for all future subdivisions in California where geologic hazards exist.

GUIDE TO THE PREPARATION OF A "SEISMICITY SECTION"

The guide that follows was submitted to the City of Los Angeles Department of Building and Safety after the earthquake by the Los Angeles Section of

Photo 15. Examples of collapse of garage unit and support under single-story unit; house to left shown in photo 14.

Photo 16. Example of collapse of single-story unit and pull-away between single and two-story portions (Almetz Street-Aldergrove Avenue). *Courtesy of the City of Los Angeles Department of Building and Safety.*

Photo 17. Example of garden wall failure (Almetz Street-Aldergrove Avenue). Note Olive View Hospital in background. *Courtesy of Charles A. Yelverton.*

Photo 18. Ground cracks associated with settlement of fill related to consolidation of underlying alluvium and/or slopewash. *Courtesy of the Engineering Geology Section, Los Angeles County Engineer's Office.*

Photo 19. Ground cracks associated with failure of materials (alluvium) under fill materials.

Photo 20. Rills from rainwash visible, but no cracks developed in fill materials or structures. Engineered fill placed under modern techniques and codes.

the Association of Engineering Geologists. It was submitted as a guide for the preparation of the "Seismicity Section" that will be required in the Engineering Geology reports that are currently required by the City of Los Angeles. The scope and geographical references can be expanded slightly, and this guide could become useful for other geographical areas.

These seismic or earthquake sections to the engineering geology reports may be requested or prepared for projects ranging in size from a single lot to a master plan for large acreage and in scope from a single-family dwelling to large engineered structures such as hospitals and high-rise buildings and for geographic sites near a potentially active fault to more remote sites. A format should be flexible in approach, method, and technique. This format permits tailoring to the appropriate scope and the opportunity for responsible additions as the state of the art improves. The investigation should be adjusted to the magnitude of the environmental factors affecting seismic risk and safety and to the intended use.

In view of the seismicity of the entire southern California area, engineering geology reports submitted to the City of Los Angeles should include seismic data which bear a relationship to the geologic stability of the landscape and the proposed structures to be placed there.

The seismic evaluation of a site for land use planning needs to be thorough enough to cover all type of potential earthquake or seismic damage but lucid enough so that it is understandable to the layman. The common earthquake-related phenomena that should be

Photo 21. Masonry structure, as noted in this picture, generally sustained greater damage than wood frame structures.

considered by the engineering geologist in his appraisal of the over-all seismic risk and safety are: (1) ground displacement along a fault, (2) ground failure (liquefaction, settlement, landsliding), and (3) ground shaking. In presenting such data, the engineering geologist should give a brief but clear description of the seismic and tectonic history of the area and for the site. In addition, attention should be given to geologic features which may adversely affect the site in the event of a large earthquake in the general area or, if probable, lesser magnitude earthquakes nearby.

Suggested Format

The seismic section of the engineering consultant's report should consider, but not be limited to, the following:

Review of the seismic and/or earthquake history of the region. This review should establish the relationship of the site to mapped faults and earthquake epicenters of significance. It may include reference to major earthquakes (both recent and historic); location

Photo 22. Example of two-story, split-level home where lack of structural support in garage portion allowed collapse. *Courtesy of the City of Los Angeles Department of Building and Safety.*

Photo 23. The one-story unit of this house settled and moved to the right following failure of the vertical (cripple) bracing between the floor and the footings. *Courtesy of the City of Los Angeles Department of Building and Safety.*

Photo 24. Note tilting and partial collapse of vertical bracings (cripples, lower right portion of structure) between floor and footing wall which allowed single-story unit to settle and move away from two-story unit.

Photo 25. Collapse of chimneys was the most prominent damage to residential structures. *Courtesy of Charles A. Yelverton.*

of epicenters of earthquakes near the site; location of the major or regional faults and a discussion of the tectonic mechanics and other relationships of significance; location of local faults and a discussion of their relationship to the regional fault pattern; evidences of local or regional fault strain and creep; pertinent parameters of ground motion and focal mechanics, if known.

It is relatively easy to justify and prepare building codes that provide great safety. The performance of single-family residential structures during the February 9, 1971, earthquake is a tribute to American science, engineering, and skills. In contrast to the two casualties out of an estimated 2.5 million living in the area of strong motion shaking from an earthquake of 6.5 magnitude, an earthquake of lesser magnitude (5.7) struck the coast of North Africa in 1960 and killed approximately one-third of those residing in the town of Agadir (casualties estimated at 11,000 out of a total population of 33,000). Many other such examples can be given for other areas of the world subject to earthquake hazards. Consequently, even though the monetary loss was high, the number of casualties and the actual percentage of loss of dwellings at San Fernando was low. An estimated 830 residential structures were demolished or required major rehabilitation out of a total of approximately 400,000 residential structures in close proximity to the earthquake, or about 0.2 percent as compared to a 30 percent to 90 percent loss by earthquakes in some other areas of the world. It should be reiterated that the greatest damage in the San Fernando earthquake occurred to the older dwellings which were built prior to the 1933 Long Beach earthquake and the development of modern codes and the Field Act. It can be assumed that almost all of the structures that sustained great damage would have withstood the effects or would have received much less damage if built to the new codes established by the City of Los Angeles. The exception to this condition would be dwellings which might be constructed directly over rupture directly associated with fault displacement.

The dangers associated with fault displacement can be essentially eliminated by proper master plan design or zoning. One of the first attempts to reduce the earthquake-fault hazard by the effective use of a master plan was the Porter Ranch development—planned in the early 1960s. The Santa Susana fault system was recognized as well as geologic indications that the fault had been active as recently as 10,000 to 11,000 years ago. Even though the code did not require that earthquake hazards be given consideration in master plan design or in engineering and engineering geology studies, the Design Engineers accepted the geologic data and recommendations that no portion of the development be placed on the upper thrust plate of the fault. Photo 28 is of the central portion of the Porter Ranch project; the Santa Susana fault system extends from right to left across the upper right portion of the photograph.

Photo 26. Motion between footings and exterior walls was often common in the areas of intense shaking.

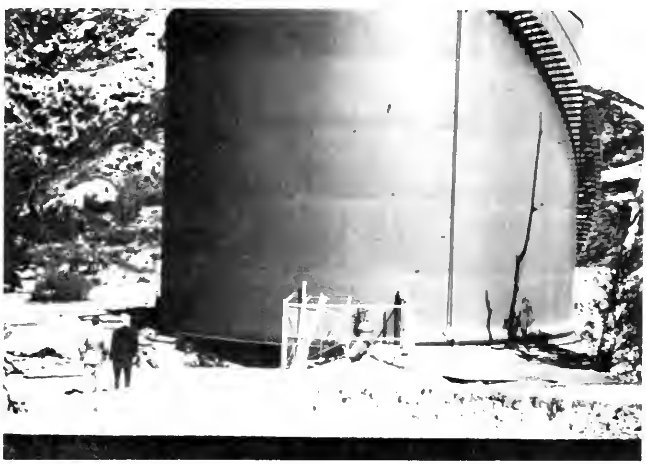


Photo 27. Photograph of Olive View Hospital water storage tank. The wrinkle at the base resulted from earthquake motion and associated water-hammer effect and vertical motion of the tank. Base plate rupture appears on right side. (Wesley G. Bruer, State Geologist, and Mason L. Hill in left foreground.)

These same geologic data were later utilized to discourage one of the major water purveyors from constructing a dam on the fault trace, with the proposed reservoir to be located on the upper thrust plate. The Sesnon Water Tank, which was severely damaged, was, however, placed approximately on the trace of the fault zone—contrary to the recommendations of the engineering geologist under contract.

It seems logical that all future designs for urban development in California should give full consideration to earthquake as well as other geologic hazards. At small added cost, man can design and construct dwellings to withstand *almost* all earthquake activity. However, he should give very detailed consideration to designing the plan so that structures are not proposed or constructed on the trace of potentially active faults, as it is currently not possible to construct dwellings that can withstand fault displacement.

Other factors that should be given careful thought while designing a master plan in earthquake-prone areas are:

1) Methods of placing engineered fill to reduce the effects of lurching. This method should include detailed soil engineering and engineering geology studies as well as supervision during construction to assure that all unsuitable materials are removed and that the fill is founded on materials which can support it so as to render the fill safe and stable. 2) Areas that may be subject to subsidence and/or consolidation, so as to avoid them as building sites unless rendered safe and stable. Generally, such areas can be readily interwoven into the greenbelt or natural preserve portions of the plan or utilized for recreational purposes. 3) Areas that possess the potential for liquefaction. 4) Topographic high areas which possess adverse geologic conditions that could become the sites of landslides, rockfalls, or other mass movements should be avoided as should the areas above and below. More than 1000 landslides of varying sizes and dimensions were triggered by the February 9, 1971, earthquake. Many of the larger ancient landslides of southern California were apparently triggered by past earthquake activity. Thus it becomes apparent that thorough soil engineering and engineering geology studies should be required for all areas possessing geologic hazards. The Turnagain Bay landslide that devastated a housing tract in Anchorage, Alaska, is a good example of what can happen and why these studies are necessary. 5) The method of placing engineered fill so as to prevent landsliding or settlement of the fill. Engineered fill should be placed in accordance with good practices and the provisions of Chapter 70 most current Edition of the Uniform Building Code. Detailed soil engineering and engineering geology investigations can be utilized to determine where and how fill materials can be safely placed.

In summary, it is possible through prudent planning or zoning to avoid the obvious hazards and eliminate or remedy other hazards. Since open space, greenbelts, and natural preserves are a part of all mod-

Photo 28. Aerial photograph of Porter Ranch trace of Santa Susana fault zone, which is located at rear of the mesa visible in upper right of photograph. The mesa will be eventually used for building, but the fault zone and area above (upper plate) will be retained as open space. *Courtesy of the City of Los Angeles Department of Building and Safety.*

ern master plans, it becomes obvious that these amenities can be designed so that the hazardous areas are not used for dwellings or other structures. Many of the areas hazardous for structures can be used for recreational and park facilities. It would be much better to have a greenbelt, bicycle trails, or parks along a potentially active fault trace rather than housing. By arranging land use to the environmental controls rather than attempting to force the environment to adjust to the plan, man can avoid many geologic hazards. We can adjust to the environment and, through science and engineering, use it effectively, efficiently, and safely. We cannot continue to force nature to adjust to man's desires.

Legislation must be passed which requires realistic and prudent use of geologic data and engineering criteria to decrease the hazards related to earthquakes. Man has the tools and knowledge to greatly increase the safety of living in California and at a very modest cost. California can be the leader in earthquake knowledge and design.

In relation to the subject of zoning, this quotation from the "Task Force on Earthquake Hazard Reduction, May 4, 1970" issued by the Institute of Governmental Studies at the University of California, Berkeley, is pertinent:

"Zoning and Police Power

4. The zoning of bays, shorelines, floodplains, wetlands and open space has established ample precedent for limiting or prohibiting land development when an important public interest is at stake. These same principles apply in the case of zoning to reduce earthquake hazards, or prevent their creation by future urban development. In addition to zoning, building code restrictions are, or course, a time-honored exercise of the police power.

5. Inadequacies in seismic safety controls are obviously not caused by a lack of legal *authority*. The real problem lies in these circumstances: (1) the primary power to regulate and enforce is lodged with the cities and counties, many of which have proven vulnerable to developmental pressures; (2) local political "will" is often lacking for the adoption of strong regulations where they are necessary; and (3) local staff capabilities are too limited to insure thorough and uniform enforcement. Consequently we cannot rely solely on local government to provide the policing required for effective earthquake-hazard reduction."

CONCLUSIONS

Even though the earthquake on February 9, 1971, damaged approximately 20,000 houses—destroying or nearly destroying 830 of them—it can be concluded that the residential structures performed extremely well from the standpoint of safety, considering the forces involved. No occupied residential structure collapsed as a result of shaking although a few were destroyed by fire. Structures overlying and immediately adjacent to zones of rupture associated with fault displacement were more greatly damaged than those a few blocks away. Single-story residential structures generally fared better than two-story homes—split level structures with the second story over the garage suffering the worst fate. Failures were generally related to the type of foundation materials in the following order: 1) Those constructed on older (pre-1963) fill which was either not properly engineered or where alluvial-slopewash was not removed prior to placement of fill were the most severely damaged; 2) those on loose alluvial foundation materials were less damaged; 3) those on semi-consolidated alluvial materials were even less damaged; and 4) those founded on properly engineered fill or bedrock were least damaged.

Revisions to building codes such as those prepared by the Technical Advisory Board for the City of Los Angeles, Department of Building and Safety (see Appendix) will improve the safety of residential development. It appears that strengthening of structures can be accomplished in design and construction at a very small increase in cost of construction.

Requirements for complete geologic and engineering studies prior to design of major engineering works or adoption of master plans will further reduce the hazards presented by earthquakes. Finally, but not least in virtue, the proper use of engineering and geologic data for zoning can be a very effective mechanism in reducing the danger to the public.

Review of the geologic features near the site that may indicate recent fault or seismic activity. The amount of detail in the study should be commensurate with the intended land use, the complexity of the area, and the seismic history. If such features exist, this review should include a field investigation of:

Location of historic or recent ground rupture or displacement along faults and location of other earthquake-induced ruptures such as are caused by lurching, settlement, and liquefaction. The evidence for existence of ground rupture should include: location, orientation, length, width, and other physical characteristics of ruptures; estimate of amount and sense of displacement on ruptures; type of faults and dating of most recent displacement including, but not limited to, inferred surface effects and estimated acceleration and age of youngest faulted unit (including soil).

Examination of stereoscopic time-lapse aerial photographs with special emphasis on fault location.

Review of survey and strain gauge records to determine if strain or creep is discernible.

Leveling records (for example, Baldwin Hills indicating area of subsidence).

Field mapping of faults, using detail commensurate with intended land use. The geologic map and/or geologic report for the site shall show or report upon any geologic features relating to the presence of faults on the site or in nearby areas (sag ponds, offset bedding, offset drainage courses, offset ridges, kerncols, shutterridges, faceted spurs, scarps, vegetation alignments). The thickness and nature of the various earth materials which affect the seismic damage potential of a site should be reported.

Review of ground water data to determine if ground-water barriers or other ground-water anomalies may suggest the presence of a fault or fault activity.

Record of earthquake damage. Analysis should be made of all site damage sustained due to shaking, surface fault rupture, or other causes related to earthquakes in historic times. Analysis may include damage factors in nearby pertinent areas.

Exploration may be required if the site is on or near an active or potentially active fault. The exploration should be tailored to the scope of the investigation, since different physical situations demand different approaches. The methods of exploration may include, but not be limited to:

1) Trenching across active fault zones and probable or possible active faults to determine width of zone, nature of zone materials, recency of movement, location of active trace within the zone, and analysis of fault plane geometry. Orientation of trenches should be shown on the geologic map; logs of trenches shall be included within the geologic report. 2) Geophysical studies which may indicate types of materials, depth to ground water, ground water anomalies, depth to bedrock, subsurface fault displacement, and dynamic properties of surficial soils and rocks including at least density and velocity. 3) Borings to determine earth materials and depth to water, to obtain samples of soil for analysis by soils engineering and geophysical surveys, and to provide additional pertinent information.

Other data that may be significant in evaluating the seismic relationship of the site and the intended land use, including but not limited to:

The types of earth materials that structures will be founded on; the distribution, thickness, and origin of surface soils, alluvium, and alluvium-like materials (this may include some poorly consolidated Plio-Pleistocene sedimentary rock materials); the depth to bedrock materials (specifically hard rock materials) and character of bedrock materials; location of the water table, variation in water levels, and such anomalies as groundwater barriers; and the topographic setting.

Graphic materials will be helpful in presenting much of the data. These materials should include: various kinds of geologic maps, cross sections, trench and borehole logs, and geophysical profiles.

For sites on or near active or potentially active fault zones, geologic investigation should be directed at determining the history of earthquake-related ground rupture, particularly displacement.

Perhaps the most important sections of the report are the conclusions and recommendations. They may be brief or very detailed. They may include but need not be limited to:

Estimate of magnitudes of earthquakes that may be generated on faults near enough to affect the site, the distance of the faults from the site, and the probable magnitude of the earthquake at the epicenter and at the site.

An over-all seismic evaluation of the site based on the history and potential for ground displacement due to faulting, ground shaking, ground rupture due to lurching, liquefaction, settlement of soils and fill, landslide activity, and failure related to high fluid pressure.

An evaluation should be presented of the geologic or engineered features that may affect the site if an earthquake should occur. These could include: steep slopes and cliffs, excavated slopes, sidehill fills, thick or deep fills, high water table, topography, and other pertinent features.

Delineation of zones of varying risk.

Determination of the potential acceleration that may affect the site, detailing the type of underlying materials (for example, bedrock, firm sediments, soft sediments, or soft, saturated sediments).

Analysis of the proposed development and/or grading considering the earth materials and an over-all geologic environment in relation to seismic potential.

Analysis of placement and/or orientation of structures, in regard to seismic potential, especially location with respect to natural geologic features; possible effect of offsite properties; possible effects of offsite engineered structures; possible effect on utilities.

These studies should be prepared by geologists, seismologists, and engineers in conformity with professional registration laws of the state.

PLANNING AND ZONING AS TOOLS IN REDUCING EARTHQUAKE HAZARD

Currently, the most efficient and effective methods of reducing earthquake dangers are: (1) to provide realistic codes or guidelines for construction such as those of the City of Los Angeles and (2) to prepare master plans for urban development that will avoid or compensate for the hazards.

APPENDIX

The following changes in the Los Angeles City Building Codes were proposed by the Technical Advisory Board for the City of Los Angeles, Department of Building and Safety, and adopted by the City Council in February 1972.

CHANGE NUMBER 1:

1. Revise Section 91.2512(e) by adding a second paragraph as follows (re: regular sheathing):
   Diaphragm sheathing connectors shall be driven flush but shall not fracture the sheathing. Approved connectors used at diaphragm boundaries and other lines of shear transfer shall provide shear, pull-out and pull-through resistance at least equal to that provided by the nails specified in this Code for the materials to be connected.
2. Revise Section 91.2512(f) by adding a second paragraph as follows (re: plywood):
   Diaphragm sheathing connectors shall be driven flush but shall not fracture the plywood. Approved connectors used at diaphragm boundaries and other lines of shear transfer shall provide shear, pull-out and pull-through resistance at least equal to that provided by the nails specified in this Code for materials to be connected.

CHANGE NUMBER 2:

1. Revise Section 91.2902(e)1, first paragraph as follows:
   (e) Ties. 1. All veneer ties shall be corrosion-resistant metal capable of resisting in tension or compression a force equal to four times the weight of the attached veneer. *In other than masonry or concrete construction the ties* shall be anchored to the wall *framing.*
   EXCEPTION: The ties required by this subsection are not required where veneer does not exceed four feet in height above the adjoining grade and the veneer backing per 91.2904(g) is provided.

CHANGE NUMBER 3:

1. Revise Section 91.4801(a) as follows:
   (a) Purpose of Division. The purpose of this Division is to provide minimum standards for safe methods of construction for *conventionally framed* wood frame dwellings, one-story masonry dwellings of brick and concrete masonry units, and accessory buildings. Masonry accessory buildings constructed under this Division shall be limited to one story in height. *Applicable portions of dwellings or accessory buildings of unusual shape, size or split levels shall be designed to resist lateral forces in accordance with other divisions of this Code.* The pro-

visions of this Division shall not be presumed to exclude any method of design or type of construction meeting all requirements of the other divisions of this Code. Where such buildings are specifically designed in accordance with other divisions of this Code, the provisions of this Division shall not apply.

CHANGE NUMBER 4:

1. Revise Section 91.4809(e) as follows:

(e) Foundation Stud Walls. **Foundation stud walls supporting one story shall be braced as required for walls in the first story of a two-story building by Section 91.4817(c) of this Division.**

Foundation stud walls **supporting two stories** shall *be braced by solid* **diagonal** *sheathing of one-inch nominal boards or ⅝-inch plywood. All edges of plywood shall be on framing or blocking.*

Sheathing **or plywood** *shall be nailed to the sills, plates, and studs but shall be ½-inch clear of the foundation concrete.* Solid blocking may be used to brace stud walls where the studs do not exceed 12 inches in height.

CHANGE NUMBER 5:

1. Revise Section 91.4817 as follows:

SEC. 91.4817—BRACING OF STUD WALLS

(a) General. Every wood stud *exterior* wall or bearing partition shall be *provided with effective bracing at least equivalent to the bracing specified in this Section.*

(b) *One-Story Buildings. Walls and partitions in one-story building shall be braced as specified in this subsection at each end, or as near the end as possible, and at least every 25 feet of its length.* Types of bracing shall be one of the following:

1. *Gypsum sheathing or wallboard not less than ½" thick covering a panel four feet wide.*
2. A one-inch by *six*-inch continuous board **extending** diagonally from bottom of lowest plate to top of upper plate at an angle sufficient to include four stud spaces;
3. Diagonal sheathing of one-inch **nominal** boards run at an angle of 45 degrees covering a panel four feet wide. Space between diagonal sheathing boards may not exceed the width of the boards;
4. A panel of plywood sheathing not less than four feet wide constructed as specified in Section 91.2512. (Wood Diaphragms and Shear Walls.)
5. Two ⅛-inch x 1½-inch steel straps placed diagonally across four stud spaces as a crossed pair of tension braces, nailed with two 8d nails at each end to top and bottom plates and two 8d nails to each intermediate stud.
6. *Gypsum lath (⅜") attached to studs and plates, and plaster (½"), covering a panel four feet wide.*
7. *Exterior stucco applied over self-furring, 3.4# expanded metal lath.*
8. *Fiberboard wall sheathing ½" thick, conforming to Division 25.*

(c) *Two-Story Buildings. Walls and partitions in the top story of a two-story building may be braced in accordance with Subsection (b) of this Section.*

1. *Twenty-five percent of the linear length of the wall or partition in braced wall sections having a minimum width of four feet when any of the following materials are used:*
   - *A. Solid diagonal sheathing of one-inch nominal boards run at an angle of 45 degrees.*
   - *B. Plywood sheathing of ⅜-inch thickness.*
   - *C. Exterior stucco applied over self-furring, 3.4# expanded metal lath.*
2. *Fifty percent of the linear length of the wall or partition in braced wall sections having a minimum width of four feet when any of the following materials are used:*
   - *A. Gypsum sheathing or wall board not less than ½" thick.*
   - *B. Gypsum lath (⅜") attached to studs and plates, covered with plaster (½").*
   - *C. Plywood sheathing of 5/16-inch thickness.*
   - *D. Fiberboard wall sheathing ½" thick conforming to Division 25.*
3. *Equivalent bracing may be provided by proportional amounts of the materials specified in 1 and 2 above.*

CHANGE NUMBER 6:

1. Revise Section 91.4818(b) and (c) as follows:

(b) Cutting and Notching. *In exterior walls and bearing partitions, any* wood stud may be cut or notched to a depth not exceeding *25% of the width of the stud.*

In non-bearing partitions, any wood stud may be cut or notched to a depth not exceeding 40% of the width of the stud.

(c) Bored Holes. A hole not greater in diameter than *40%* of the stud width may be bored in a wood stud.

Bored holes not greater than 60% of the width of the stud are permitted in non-bearing partitions or in any wall where each bored stud is doubled provided not more than two such successive doubled studs are so bored.

In no case shall the edge of the bored hole be nearer than ⅝-inch to the edge of the stud.

Bored holes shall not be located at the same section of stud as a cut or notch.

CHANGE NUMBER 7:

1. Revise Section 91.4822(e)5a. and b. as follows:

5. Reinforcement. Every masonry or concrete chimney shall be reinforced with steel consisting of the following.

Vertical reinforcement shall be #4 deformed bars hooked into the footing and spaced at not greater than 24-inches on center around the chimney. In chimneys of 40-inch width or less, four of the vertical bars shall be continuous for the full height of the chimney and be hooked into the chimney cap. Such continuous bars shall be located as near the corners of the chimney as practicable and bends in the bars shall be avoided or minimized. Two additional vertical bars shall extend full height for each additional flue in the chimney or for each additional 40-inches or fraction of chimney width. Bars which are not required to be continuous shall extend from the footing to not less than 36 inches above the level of the smoke shelf.

EXCEPTION: Chimneys constructed of hollow masonry units may have vertical reinforcing bars spliced to footing dowels, provided that called inspections are made in compliance with the requirements of Division 24 of this Article for filled cell construction.

b. *#3* horizontal bars as ties looped around vertical bars and spaced at not more than 24 inches apart vertically from footing to chimney cap. *A tie shall also be provided at each bend in vertical bars;*

CHANGE NUMBER 8:

1. Revise Section 91.4822(j) and (k) as follows:

(j) Anchorage. All masonry and concrete chimneys shall be anchored at each floor or ceiling line more than six feet above grade, except when constructed completely within the exterior walls of the building. Anchorage shall consist of two 3/16-inch by one inch steel straps cast at least 18 inches into the chimney *with a 180 degree bend with a six inch extension around the vertical reinforcing bars in the outerface of the chimney. Each strap shall be* fastened to the structural framework of the building with two ½ inch bolts per strap. Where the joints do not head into the chimney the anchor straps shall be connected to *two-inch by four-inch ties crossing a minimum of four joists. The ties shall be connected to each joist with two 16d nails.* Metal chimneys shall be anchored at each roof and ceiling with two 1½ inch by ⅛ inch metal straps looped around the outside of the chimney insulation and nailed with six 8d nails per strap to the roof or ceiling framing.

(k) Cutting of Plates. Where plates are cut to permit the passage of the chimney, $\frac{3}{16}$-inch by one-inch steel strap anchors shall be hooked into the concrete bond beam and secured to the end of each plate with at least two ½ inch by *four* inch lag screws-*or* two ½-inch bolts.

CHANGE NUMBER 9:

1. *Revise* Rule of General Application RGA 661—Lateral Load

(g) *Anchorage of Water Heaters. Water heaters having non-rigid water connections and over four feet in height from the base to the top of the tank case shall be anchored or strapped to prevent horizontal and vertical displacement due to earthquake.*

CHANGE NUMBER 10:

1. *Revise* Rule of General Application RGA 661—Lateral Load Distribution Through Rotation of Wood Diaphragms—*as* shown below.

RULE OF GENERAL APPLICATION—RGA 661

SUBJECT: Rotation of Wood Diaphragms *in Buildings Designed by Division 48*—RR 22829

Later loads may be distributed by rotational effect in **one-story wood frame buildings having wood roof diaphragms designed under the provisions of Division 48 of the Code** with the following limitations:

$$d = 25' \text{ Max.}$$

$$L \gtreqless d$$

1. One-story buildings without basements when the length is greater than the width and the open front is located in the longer wall.

Section 2

Seismology

CHAPTER 20

Seismological Studies of the San Fernando Earthquake and Their Tectonic Implications[1]

by Clarence R. Allen,[2] Thomas C. Hanks,[2] and James H. Whitcomb [2]

ABSTRACT

Improved hypocentral locations have been obtained for the San Fernando earthquake and its larger aftershocks through the use of data from portable stations installed in and around the aftershock area subsequent to the main shock. The main shock, at 14 00 41.8 GMT on 9 February 1971, is now assigned a magnitude (M_L) of 6.4 and a location at 34° 24.7′ N, 118° 24.0′ W, h = 8.4 km. Fifty-five aftershocks of magnitude 4.0 and greater had occurred through 31 December 1971. The lunate-shaped epicentral distribution of aftershocks is consistent with the idea of southward thrusting along a disc-shaped fault surface, and aftershock depths as well as aftershock focal mechanisms suggest that the thrust surface dips about 35° toward N 20° E. However, a distinct linear alignment of left-lateral strike-slip aftershocks parallel to the motion direction near the west boundary of activity suggests that the fault surface has a steep flexure along this line, down-stepped to the west, and both the planar distribution of aftershocks and the local geology support this concept.

The purpose of this paper is to describe the seismologic aspects of the San Fernando earthquake of 9 February 1971 and its aftershocks and to interpret these earthquakes in terms of a tectonic model of the associated faulting. Several reports on these subjects were prepared by the authors within 3 weeks following the earthquake (Allen *et al.*, 1971; Hanks *et al.*, 1971; Whitcomb, 1971; Division of Geological and Planetary Sciences, 1971), and this paper updates these studies utilizing information recorded by the Caltech network through 31 December 1971. By this time, the principal aftershock activity seems to have concluded, although small aftershocks still continue. During the seismological investigations, particular effort has been made to gain an understanding of the tectonic mechanism of the earthquake—the configuration of the fault surface, the source mechanism of the main shock and aftershocks, and the tectonic environment of the faulted region. Preliminary conclusions on these topics are summarized herein, although it should be recognized that studies are vigorously continuing, and much detailed substantiating evidence as well as possible modifications will be presented in subsequent papers.

SEISMOLOGIC ENVIRONMENT

In the years prior to 1971, the San Fernando area was characterized by low to moderate seismic activity not unlike that of many other parts of southern California. Indeed, the 1934–1963 strain-release maps (Allen *et al.*, 1965) indicated that the northern San Fernando Valley was seismically less active than most other parts of the greater Los Angeles area. Nothing that has been recognized in the very recent seismic history seems to suggest that this area, more than any other area, was particularly likely to experience a magnitude 6.4 earthquake. It should be kept in mind, however, that an earthquake of at least this magnitude occurs somewhere in the southern California region on the average of about once every 4 years (Allen *et al.*, 1965), and in this sense the San Fernando earthquake was no great surprise. An earthquake of this same magnitude occurred in 1968 in the Borrego Mountain area 220 km southeast of Los Angeles, but damage was small because—unlike the 1971 event—it occurred in a remote location.

Between 1934 and 1971, which is the interval during which epicentral locations of southern California earthquakes have been listed by the California Institute of Technology, only about ten earthquakes of magnitude 3.0 and greater occurred in the area that corresponds to the epicentral region of the San Fernando earthquake (Figures 1, 2). Prior to 1934, however, one earthquake is of special importance; this is the so-called Pico Canyon earthquake of 1893 (Townley and Allen, 1939), which was apparently centered only slightly west of the 1971 epicenter and was of only slightly lesser magnitude. It does indicate, significantly, that moderate earthquakes of this size were not unknown in the region.

Although most of the faults of the San Fernando area had not been generally recognized by geologists and seismologists as "active" prior to 1971, abundant unpublished evidence indicated that some were active. Particularly along the Tujunga segment of the San Fernando fault, geologists of the Metropolitan Water District had—long before the earthquake—carefully

---

[1] Contribution No. 2124, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena. Manuscript submitted to the California Division of Mines and Geology January 24, 1972.

[2] Seismological Laboratory, California Institute of Technology.

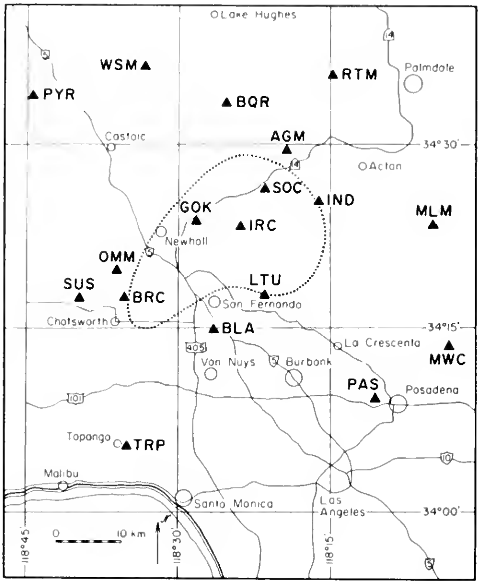


Figure 1. **Aftershock area of the San Fernando earthquake (dotted line), showing locations of seismograph stations (triangles) that were used in the epicentral locations of this study. Station data are given in table 1.**

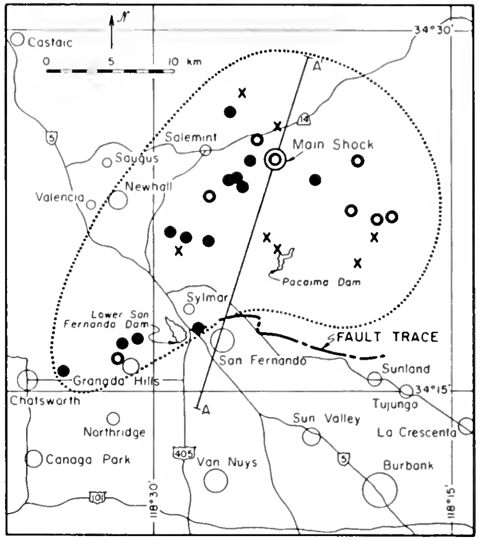


Figure 2. **Earthquakes of the San Fernando series of magnitude 4.0 and greater through 31 December 1971. Solid circles represent "A" locations (see text), open circles "B" locations, and heavy X's "C" locations. Dotted line shows limits of most aftershock activity, including many smaller shocks than those shown. Cross section A–A' is shown in figure 4.**

documented the thrusting of older rocks over very young gravels (Proctor *et al.*, 1972), along the same fault which broke on 9 February. On the other hand, such evidence of geologically very recent displacements is becoming more and more widespread along many faults in coastal California, and there was no known reason to have picked out the San Fernando fault more than many others as being a particularly likely candidate for an earthquake in 1971. The lesson is clear: until we gain better geologic and seismologic understanding of the relative activity of various fault zones, all of coastal California must be considered to be one of relatively high earthquake hazard.

HYPOCENTRAL LOCATIONS

In our earlier papers, Allen *et al.* (1971) summarized the seismological data of the first 3 weeks based only on the permanent stations of the Caltech network, while Hanks *et al.* (1971) located much more precisely a number of aftershocks during a particular 18-hour period on the basis of Caltech portable stations installed in the epicentral region within a few hours of the main shock. In this paper, we attempt to use data from the Caltech portable stations, in addition to those of several other agencies (table 1, figure 1) to establish correction factors to make more effective use of the more-distant permanent stations that were the only source of seismic information during the first few hours when the great bulk of aftershock activity occurred as well as later in the aftershock sequence when most of the portable stations had been removed. For the purpose of presenting a homogeneous body of data, only shocks of magnitude 4.0 and greater have been listed in table 2 and portrayed in figure 2. We feel that this listing is relatively complete even within the first few minutes following the main shock, for which we relied heavily on the low-gain (4x, 100x) instruments of the Pasadena network, as well as on the remarkable 6-minute-long accelerograph record from Pacoima Dam (Trifunac and Hudson, 1971).

Twenty-two aftershocks of magnitude 3.5 and greater that were particularly well located by the portable stations were used to establish correction factors for the more-distant permanent stations. In general, the portable stations that were used included most of the CIT and EML stations (table 1), as well as the three USGS indicated stations for a more limited number of shocks. Although the more-distant stations of the Caltech network (those indicated by an asterisk in table 1) were not used in the precise locations, time residuals at these stations were calculated in each case, and the average travel-time correction factors thus obtained for these and the other permanent stations are as follows:

PAS	+.2 sec
MWC	—.1
PYR	—.2

Table 1. Seismographic stations whose data were used in epicentral locations shown on figure 2 and in table 2. Stations indicated by asterisks are distant stations used only for locations of shocks during first few hours, before temporary stations were established. Agency designations are: CIT, California Institute of Technology; DWR, California Department of Water Resources; EML, Earthquake Mechanism Laboratory of NOAA; UCSD, University of California at San Diego; USGS, National Center for Earthquake Research of the U.S. Geological Survey. Distance is that to hypocenter of main shock.

Station		Agency	North Latitude	West Longitude	Distance (km)	Period of operation
AGM	Agua Dulce	EML	34 29.5	118 19.3	14.7	2/10–4/24
BLA	Blayney	CIT	34 18.8	118 26.7	20.6	3/02–present
BQR	Bouquet Canyon	CIT	34 33.5	118 25.5	18.9	2/09–5/07
BRC	Brown's Canyon	CIT	34 17.6	118 35.4	23.5	2/09–5/07
CSP*	Cedar Springs	DWR	34 17.9	117 21.5	97.2	permanent
GOK	Golden Oak Ranch	CIT	34 23.1	118 28.3	11.4	2/10–5/06
GSC*	Goldstone	CIT	35 18.1	116 48.3	176.1	permanent
IND	Indian Canyon	CIT	34 25.2	118 16.2	15.2	2/10–4/22
IRC	Iron Canyon	CIT	34 23.3	118 23.9	9.3	2/09–5/07
ISA*	Isabella	CIT	35 38.6	118 28.6	139.0	permanent
LTU	Little Tujunga	UCSD	34 17.7	118 21.6	16.0	2/09–2/11
MLM	Mill Creek Summit	EML	34 23.4	118 04.8	31.2	2/10–4/24
MWC	Mount Wilson	CIT	34 13.4	118 03.5	39.1	permanent
OMM	Oat Mountain	EML	34 19.8	118 36.0	22.5	2/25–4/22
PAS	Pasadena	CIT	34 08.9	118 10.3	37.0	permanent
PLM*	Palomar	CIT	33 21.2	116 51.7	184.5	permanent
PYR	Pyramid	DWR	34 34.1	118 44.5	37.1	permanent
RTM	Ritter Ranch	EML	34 35.8	118 14.8	26.7	2/10–4/22
RVR*	Riverside	CIT	33 59.6	117 22.5	105.6	permanent
SBLG	Laguna Peak	USGS	34 06.6	119 03.9	70.2	permanent
SOC	Soledad Canyon	CIT	34 26.1	118 21.7	10.0	2/10–5/06
SUS	White Oaks Park	USGS	34 17.3	118 39.8	29.0	2/12–4/24
SYP*	Santa Ynez Peak	CIT	34 31.6	119 58.7	145.5	permanent
TRP	Trippet Ranch	USGS	34 05.4	118 35.1	40.4	2/12–4/24
WSM	Warm Springs	EML	34 36.4	118 33.5	27.6	2/10–4/24

SYP	+.6
ISA	+.5
GSC	+.2
CSP	+.1
PLM	+1.3

In addition, correction factors were applied to some of the portable stations in the southwestern part of the aftershock region, where considerable thicknesses of alluvium and sedimentary rocks are locally present, as contrasted to the basement rocks that closely underlie most of the rest of the area. These correction factors, based on the local geology, were: BLA, —.5; BRC, —.3; OMM, —.3; SUS, —.2; LTU, —.2 sec. All of the above travel-time correction factors were applied to a computer-location program based on the three-layer southern California crustal model of Press (1960). In actuality, this model is clearly a gross oversimplification; in their explosion calibration of the US Geological Survey network in this same area, Wesson and Gibbs (1971) demonstrated that the local geology and crustal structure are very complicated and variable.

One effect of using both the travel-time correction factors and the larger number of close-in stations has been to assign generally shallower hypocentral depths than those obtained earlier. Thus, for example, the hypocenter of the main shock is now assigned a depth of 8.4 km (table 2) instead of the earlier 13.0 km (Allen *et al.*, 1971), although the effect on the location of the epicenter is less than 1 km.

Hypocenters obtained in this study have been divided into three categories of accuracy (table 2), depending on the number and location of stations used in the solution and on the standard error of the computer solution. We feel that "A"-quality locations are generally accurate to within 2 km horizontally and 4 km vertically. "B"-quality hypocenters are felt to be accurate to within 4 km horizontally and 8 km vertically; and "C"-quality solutions are still less accurate. Those hypocentral locations in the vicinity of the main shock probably are much better than these standards, and the depths of the deeper shocks are more accurately determined than those of shallow focus. The figures represent somewhat subjective but conservative judgments based on attempts at location under a wide variety of assumptions, as well as on the comparison of some of our solutions with the largely independent US Geological Survey solutions based on explosion calibration (R. Wesson, personal communication).

Because of the difficulty in obtaining hypocentral solutions for the numerous large aftershocks that occurred within the first 10 minutes following the main shock (table 2), it is dangerous to attempt to draw conclusions about possible migrations in aftershock activity with time. It nevertheless may be significant that all of the larger aftershocks that we have located in the southwestern extremity of the aftershock zone —near Chatsworth and Granada Hills (figure 2)— occurred relatively late in the aftershock period. The largest flurry of activity started almost 2 months after the main shock and included the shallow magnitude

Table 2. Shocks of the San Fernando series of magnitude 4.0 and greater, 9 February 1971 through 31 December 1971. For meaning of "Quality" see text.

Date	*Time (GCT)*	*North latitude*	*West longitude*	*Depth (km)*	*Quality*	*Magnitude*
2 09	14 00 41.8	34 24.7	118 24.0	8.4	B	6.4
2 09	14 01 08					5.8
2 09	14 01 33					4.2
2 09	14 01 40					4.1
2 09	14 01 50					4.5
2 09	14 01 54					4.2
2 09	14 01 59					4.1
2 09	14.02 03					4.1
2 09	14.02 30					4.3
2 09	14 02 31					4.7
2 09	14 02 44					5.8
2 09	14 03 25					4.4
2 09	14 03 46					4.1
2 09	14 04 07					4.1
2 09	14 04 34					4.2
2 09	14 04 39					4.1
2 09	14 04 44					4.1
2 09	14 04 46					4.2
2 09	14 05 41					4.1
2 09	14 05 50					4.1
2 09	14 07 10					4.0
2 09	14 07 30					4.0
2 09	14 07 45					4.5
2 09	14 08 40					4.0
2 09	14 08 07					4.2
2 09	14 08 38					4.5
2 09	14 08 53					4.6
2 09	14 10 21.5	34 21.3	118 19.0	−2.0	C	4.7
2 09	14 10 28					5.3
2 09	14 16 12.9	34 20.3	118 19.9	11.1	C	4.1
2 09	14 19 50.4	34 21.4	118 24.4	11.8	C	4.0
2 09	14 34 36.1					4.9
2 09	14 39 17.7	34 20.9	118 23.9	7.0	C	4.0
2 09	14 40 17.4	34 26.0	118 23.9	−2.0	C	4.1
2 09	14 43 47.5	34 20.8	118 28.9	5.9	C	5.2
2 09	15 58 20.9	34 22.5	118 20.1	9.0	B	4.8
2 09	16 19 26.5	34 27.4	118 25.6	−1.0	C	4.2
2 10	03 12 12.0	34 22.2	118 18.1	.8	B	4.0
2 10	05 06 35.7	34 24.7	118 19.8	4.7	B	4.3
2 10	05 18 07.2	34 25.5	118 24.9	5.8	B	4.5
2 10	11 31 34.6	34 23.1	118 27.3	6.0	B	4.2
2 10	13 49 53.7	34 23.9	118 25.1	9.7	A	4.3
2 10	14 35 26.7	34 21.7	118 29.2	4.4	A	4.2
2 10	17 38 55.1	34 23.8	118 22.0	6.2	A	4.2
2 10	18 54 41.7	34 26.7	118 26.2	8.1	A	4.2
2 21	05 50 52.6	34 23.8	118 26.3	6.9	A	4.7
2 21	07 15 11.8	34 23.5	118 25.6	7.2	A	4.5
3 07	01 33 40.5	34 21.2	118 27.4	3.3	A	4.5
3 25	22 54 09.9	34 21.4	118 28.5	4.6	A	4.2
3 30	08 54 43.3	34 17.7	118 27.8	2.6	A	4.1
3 31	14 52 22.5	34 17.2	118 30.9	2.1	A	4.6
4 01	15 03 03.8	34 24.7	118 25.2	7.1	A	4.2
4 02	05 40 25.1	34 17.0	118 31.7	3.0	A	4.0
4 15	11 14 32.0	34 15.9	118 34.6	4.2	A	4.2
4 25	14 48 06.5	34 22.1	118 18.9	−2.0	B	4.0
6 21	16 01 08.5	34 16.4	118 31.9	4.1	B	4.0

4.6 shock of 31 March that locally caused more damage in Granada Hills than did the main shock itself (Barrows *et al.*, this volume).

MAGNITUDES

The local magnitude (M_L) of the San Fernando earthquake main shock was tentatively given as 6.6 by Allen *et al.* (1971) and Division of Geological and Planetary Sciences (1971) on the basis of initial examination of the low-gain (4x) Wood-Anderson NS seismogram written at Pasadena. Subsequently, other low-gain instrumental records of the Pasadena network have been examined in detail, and we herein update our original estimate of M_L on the basis of records from Riverside, Cottonwood, and Santa Barbara, in addition to Pasadena. All normal-magnification (2800) Wood-Anderson instruments were off-scale, such as those at Barrett and Tinemaha. Resulting magnitude assignments from the various low-gain instruments are as follows:

Pasadena	NS	4x	$M_L = 6.7$
Riverside	NS	4x	6.5
Santa Barbara	EW	100x	6.3
Cottonwood	NS	100x	6.3
Cottonwood	EW	100x	6.3

The Pasadena determination is subject to the additional uncertainty that the $-\log A_0$ correction (Richter, 1958) is a very sensitive function of distance for epicentral distances of less than 50 km.

On the basis of these determinations, we assign $M_L = 6.4$ to the San Fernando earthquake. This compares closely to the mean magnitude of 6.48 assigned by Bolt and Gopalakrishnan (this volume) from four stations of the Berkeley network. The PDE listing by the National Earthquake Information Center of NOAA is $M_S = 6.2$, $m_b = 6.5$, based on 279 stations reporting.

Magnitudes have been assigned to aftershocks (table 2) on the basis of readings from eleven standard Wood-Anderson torsion seismometers at six widely spaced stations of the southern California network (Pasadena, Barrett, Cottonwood, Riverside, Santa Barbara, Tinemaha). Most magnitudes have been determined by averaging the readings from at least five of these stations. It is significant, however, that the average standard deviation for individual station readings for 20 aftershocks of magnitude 4.0 and greater, each recorded at five or more stations, was 0.30. Considering this large variation observed on standard instruments in a wide variety of azimuths from the epicenter, some of the discrepancies between Caltech and Berkeley magnitudes reported by Bolt and Gopalakrishnan (this volume) are not surprising.

FOCAL MECHANISMS AND TECTONIC INTERPRETATIONS

Fault-plane solutions for the main shock have been carried out independently by several investigators (Canitez and Toksoz, in press; Dillinger and Espinosa, 1971; Wesson *et al.*, 1971; Whitcomb, 1971a), and they agree that the basic mechanism of initial faulting was that of a thrust striking about N 70° W, dipping about 50° NE, and including a significant component of left-lateral slip in addition to the thrust component. This agrees remarkably well with the surface observations of faulting in the Sylmar-San Fernando area, some 13 km farther south. Kamb *et al.* (1971), for example, report the overall trend of the surficial fault break to be N 72° W with north dips averaging about 42°; they also report "nearly equal amounts of north-south compression, vertical uplift

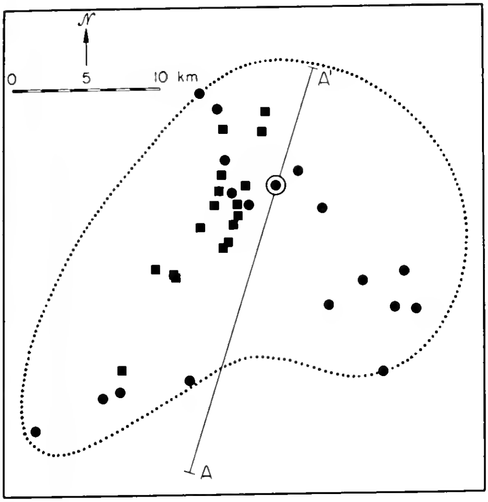


Figure 3. Earthquakes of "A" and "B" hypocentral accuracy (see text) for which good fault-plane solutions have been obtained indicating either left-lateral strike slip on north-striking planes (squares) or thrusting on north-dipping planes (circles). A number of epicenters are shown here that are not on figure 2 because some earthquakes down to magnitude 3.0 have been included. Dotted line is same as in figures 1 and 2.

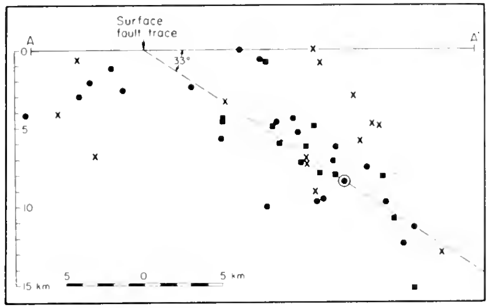


Figure 4. Vertical cross section along line A–A' of figures 2 and 3, with hypocenters projected into the plane of section. Symbols are the same as in figure 3, except that additional small crosses indicate well located earthquakes for which ambiguous or transitional fault-plane solutions have been obtained.

(north side up), and left-lateral slip."

The hypocentral locations of the main shock and aftershocks presented herein support the idea of displacement on a north-dipping thrust fault, and it seems particularly likely that the lunate distribution of aftershock epicenters (figures 2, 3; Allen *et al.*, 1971; Hanks *et al.*, 1971; Wesson *et al.*, 1971) reflects the edge of the disc-shaped segment of the fault plane that slipped during the earthquake, where stresses remained high following the main shock. Very few aftershocks occurred in the vicinity of the surface break, presumably because stresses were completely relieved there. Two principal areas of interest remain: (1) aftershocks near Granada Hills and Chatsworth, at the southwest end of the aftershock zone (figure 2), are south of the projected trace of the thrust fault and therefore do not fit so simple a picture of thrusting; and (2) focal-mechanism studies of aftershocks (Whitcomb, 1971a, 1971b) include many shocks of strike-slip character that demand an explanation more complicated than that of a simple thrust surface.

Disregarding momentarily those aftershocks near Granada Hills and Chatsworth, it is clear from figure 4 that the average dip of the zone of faulting north from the fault trace is considerably less than the 50° dip indicated by the focal mechanism of the main shock. One might explain this by systematic errors in the depth assignment of the hypocenters shown in figure 4, but substantiating evidence of the relatively shallow dip of the fault zone is given by the motion vectors of individual focal-mechanism solutions. For some 65 aftershocks, the motion vectors closely concentrate around an average plunge of 36° toward N 20° E, which corresponds closely to the dip of the hypothetical fault surface passing through the hypocenter of the main shock and the main concentration of aftershock hypocenters (figure 4). We prefer to believe, therefore, that the steep dip of the fault plane portrayed by the focal mechanism of the main shock represents only the very initial motion, and that the fault displacement then propagated to the surface along a zone dipping some 15° less steeply. The focal-mechanism data on which this and the following arguments are based will be presented in detail in a separate paper by Whitcomb; the principal ideas have already been presented in Whitcomb, 1971a and 1971b.

It is clear from figure 3 that the aftershocks of dominantly strike-slip character delineate a relatively well-defined north-trending zone west of the epicenter of the main shock. If rhe solutions portrayed right-lateral slip, this zone might be visualized as a typical tear fault (Hills, 1963) extending toward the ground surface, but their consistent portrayal of left-lateral slip demands instead that the thrust surface turn *downward* along this zone. These strike-slip earthquakes typically occur on fault surfaces dipping steeply westward, and we thus visualize a linear, steep flexure in the fault surface along this zone (figure 5). Under this hypothesis, most of the strike-slip aftershocks should be deeper than the thrust aftershocks to the east, and this is permitted but not demanded by the data of figure 4. It is significant, however, that all but one of the few thrust-type aftershocks deeper than the main shock (figure 4) occur within and west of the flexural zone, suggesting that the flexure is in essence a north-plunging, steep-flanked monocline that simply steps down the thrust plane to a somewhat greater depth west of the flexure, perhaps by 3–5 km.

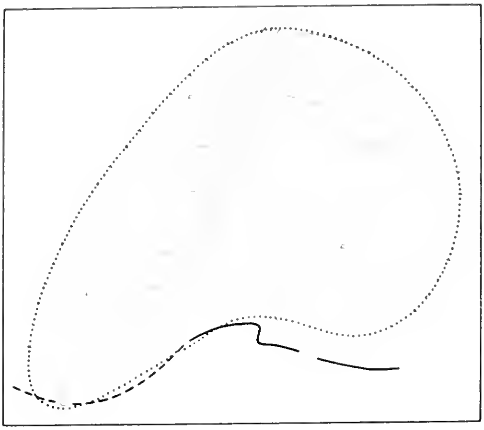


Figure 5. Schematic structural contour map showing simplified contours, in kilometers, on fault plane and showing monoclinal flexure that might explain strike-slip aftershock mechanisms on steep west-dipping flank of flexure in fault surface.

If indeed a flexure exists along the zone of strike-slip aftershocks, one geometric effect would be to displace the trace of the thrust fault to the south on the west side of the flexure (figure 5), and this may be the explanation of the aftershocks near Granada Hills and Chatsworth that are south of the trace of the fault as projected westward from the Sylmar and Tujunga segments. Furthermore, their predominant thrust-type focal mechanisms are consistent with their being west of the flexure, in analogy to those thrust-type aftershocks at the very northwest corner of the aftershock area (figure 3). It is also significant that all of the thrust-type aftershocks west of the flexure seem to have occurred well after the initiation of aftershock activity, on or after 11 February; the larger shocks in the Chatsworth-Granada Hills area (figure 2) all occurred after 30 March very late in the aftershock period.

Further support for the existence of a north-trending flexure comes from the mapped geology of the area (Wentworth and Yerkes, 1971, figure 2). The trace of the Santa Susana thrust, which lies parallel to and some 4 km north of the San Fernando fault, makes a distinct bend north of Granada Hills in exactly the manner postulated for the San Fernando fault (figure 5). Furthermore, the fact that basement rocks are widely exposed in the San Gabriel Mountains east of this zone, whereas only younger sedimentary rocks are exposed to the west, strongly supports the concept of a flexural down-step to the west in this area.

Thus we argue that the San Fernando earthquake was caused by displacement on a thrust fault or zone of thrust faults dipping about 35° north and striking about N 70° W. Particularly where the fault trace trended more westerly, as along the Sylmar segment, significant left-lateral slip occurred. A steep flexure in the thrust-fault surface, parallel to (and probably controlling) the direction of slip and down-stepped to the west, tended to limit the zone of initial breaking on the west and led to numerous aftershocks of left-lateral strike-slip character on the steep west-dipping flank of the flexure. Some thrust displacement occurred later on the down-stepped segment of the thrust fault west of the flexure, as indicated by aftershocks in the Chatsworth-Granada Hills area and in the northwestern extremity of the aftershock zone north of Solemint. Whitcomb (1971a; 1971b) has pointed out that many of the aftershocks east of the main epicenter have fault-plane solutions which are consistent with normal faulting along steep northwest-trending faults; for simplicity, such shocks have not been shown on figures 3 and 4, but these events agree with the concept of compressional release resulting from a southward thrust toward the San Fernando Valley.

ACKNOWLEDGMENTS

We are particularly indebted to many other agencies and persons for supplying data from their portable stations that have been used in our study: Earthquake Mechanisms Laboratory, NOAA (Don Tocher); National Center for Earthquake Research, USGS (Robert Wesson, Willy Lee); University of California at San Diego (James Brune); California Department of Water Resources (Paul Morrison). At Caltech, Gladys Engen, Mark Gaponoff, Jan Garmany, and John Nordquist read many of the records and carried out many of the computer solutions. This study was supported by the Caltech Earthquake Research Affiliates and by the National Science Foundation (Grant GA29920).

CHAPTER 21

Magnitudes, Aftershocks, and Fault Dynamics[1]

by Bruce A. Bolt[2] and B. S. Gopalakrishnan[3]

MAGNITUDE OF THE MAIN SHOCK

The principal shock occurred at 14h 00m 41.6s (GMT) near latitude 34° 24.0′ N and longitude 118° 23.7′ W. The focal depth was calculated to be 13 km (hypocenter determination by Allen *et al.*, 1971). A later computation by Allen *et al.* (1972) gives a depth of 8.4 ± 4 km. Because of the size and proximity of the main shock, the Richter magnitude could not be assessed directly by the California Institute of Technology network of Wood-Anderson seismographs. The readings of the Wood-Anderson seismographs of the Berkeley network are given in table 1. In previous work, small additive adjustments were derived empirically to make California Institute of Technology and Berkeley magnitudes agree numerically. These adjustments, shown in table 1, were applied.

Table 1. Data from the Wood-Anderson seismographs of the Berkeley network.

Station	Epicentral distance (km)	Azimuth (degrees)	Amplitudes (mm)		Magnitude	Correction	Corrected magnitude (M)
			E–W	N–S			
BRK	519.1	319.0	55.0	57.0	6.5	0	6.5
MHC	438.7	319.0	57.5	17.5	6.2	+0.1	6.3
MIN	718.4	337.6	26.5	21.7	6.6	−0.1	6.5
ARC	876.1	326.8	11.0	10.6	6.4	+0.2	6.6

The resulting mean Richter magnitude is 6.48 ± 0.15. The magnitude calculated by Allen *et al.* (1972) from five strong-motion seismographs of the Pasadena network is 6.4.

LIST OF AFTERSHOCKS

The short-period seismographs of the Berkeley telemetry network are sensitive enough to detect all the aftershocks in the San Fernando Valley region down to magnitude 2.8. The most sensitive are the vertical Benioff seismographs at Priest ($\Delta = 282.8$ km) and Jamestown ($\Delta = 434.4$ km); the Wood-Anderson seismographs at Mt. Hamilton and Berkeley yield a complete set of aftershocks only down to magnitude 4.0. Since a uniform magnitude list was the essential aim, a magnitude threshold of 4 was adopted. An amended list of aftershocks down to small magnitudes based on California Institute of Technology readings may be found in Allen *et al.* (1972). The complete list of aftershocks of magnitude greater than 4 is given in table 2.

Table 2. Aftershocks of magnitude ≥ 4.0 from Wood-Anderson seismographs of the Berkeley network, from February 9 (14 h 10m) through June 21.

Date	Approximate origin time	Number of stations used	Mean magnitude	California Institute of Technology magnitude
Feb. 9	14:10:28	--	--	5.3
	14:16:11	--	--	4.1
	14:19:50	2	4.1	4.0
	14:34:36	4	5.2	4.9
	14:43:47	3	4.7	5.2
	15:58:23	4	5.0	4.8
	16:19:29	3	4.5	4.2
10	03:12:13	3	4.1	4.0
	05:06:37	3	4.5	4.3
	05:18:07	3	4.7	4.5
	11:31:35	3	4.4	4.2
	13:49:54	3	4.6	4.3
	14:35:27	3	4.4	4.2
	17:38:55	3	4.3	4.2
	18:54:41	3	4.4	4.2
15	08:04:49	3	4.3	3.9
20	23:15:58	3	4.2	3.3
21	02:42:17	3	4.2	3.2
	05:50:52	3	4.7	4.7
	07:15:12	3	4.5	4.5
Mar. 7	01:33:41	3	4.8	4.5
	06:57	3	4.4	--
25	22:54:10	3	4.5	4.2
30	08:54:43	3	4.6	4.1
31	14:52:23	3	5.0	4.6
Apr. 1	15:03:04	3	4.5	4.2
15	11:14:32	3	4.6	4.2
25	14:48:06	3	4.5	4.0
June 21	16:01:09	3	4.2	4.0

It should be pointed out that there is not always an agreement between the magnitudes given in table 2 and those of Allen *et al.* (1971) given in the last column of the table. Some earthquakes assessed at $M_L \geqslant 4.0$ at California Institute of Technology were recorded with smaller magnitudes at Berkeley and Mount Hamilton. The greatest discrepancy is for the earthquake of February 21, 1971, (Origin time 02:42: 17 GMT) for which the Berkeley magnitude is 4.2

[1] Manuscript submitted for publication October 6, 1971.
[2] Seismograph Station, University of California, Berkeley.
[3] The junior author died suddenly on September 26, 1971, after having worked closely with Dr. Bolt on the preparation of this paper, which stands as a monument in memory of B. S. Gopalakrishnan.

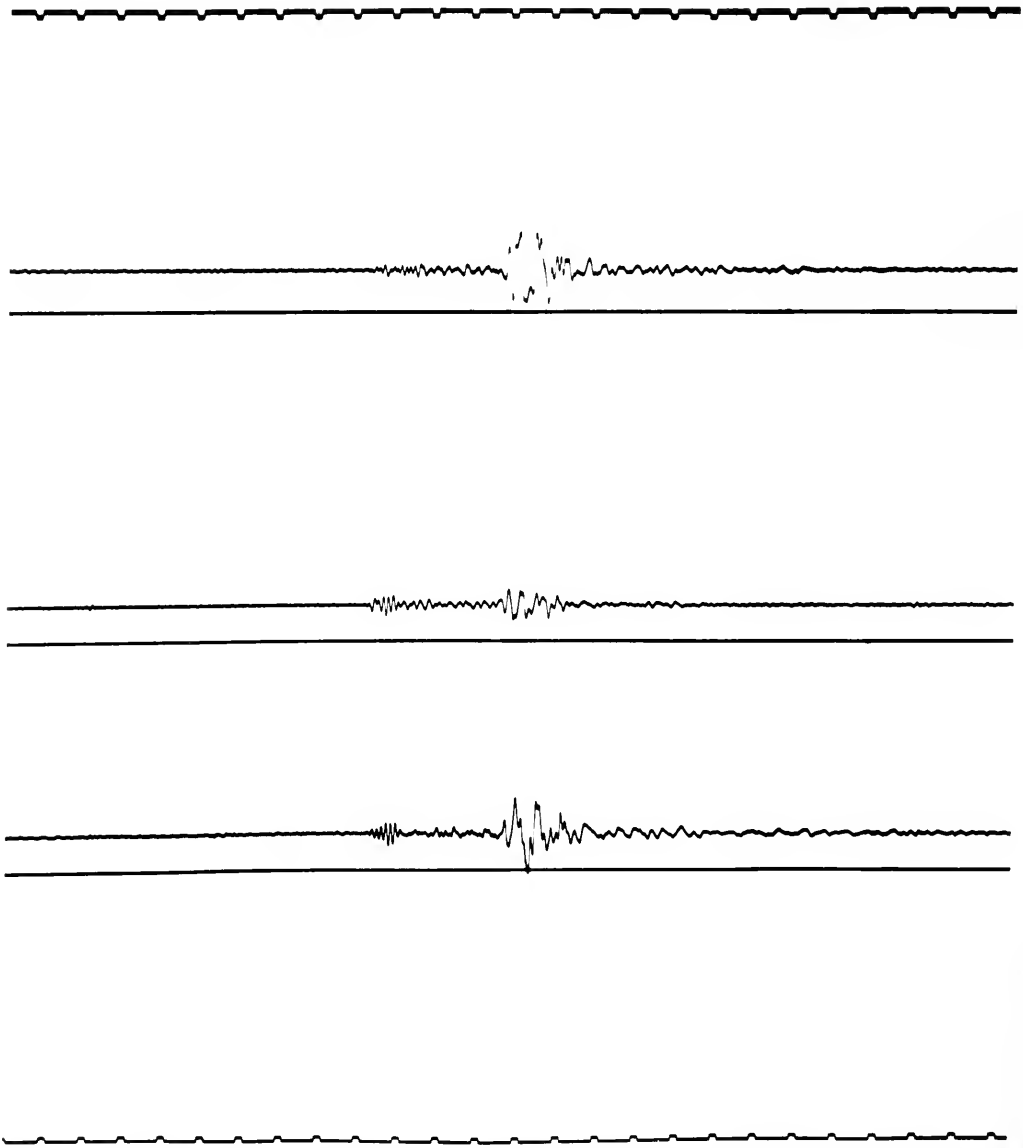


Figure 1. Three-component accelerogram of the aftershock at 14h 02m 48s. The top trace is S 74° W; the central trace is vertical (down); and the bottom trace is S 16° E. Time marks are half seconds on the top and bottom trace.

and the California Institute of Technology magnitude is given as 3.2.

Aftershocks in the list in table 2 began about 10 minutes after the main shock. Prior to 14h 10m, the records of the seismometers were too disturbed to allow separation of events. Fortunately, the Pacoima strong-motion accelerometer continued to record for about 7 minutes after being triggered by the main shock (Maley and Cloud, 1971), making it possible to study the aftershocks in the first 7 minutes following the main shock. Table 3 lists these aftershocks. The magnitudes were computed by taking the magnitude of the main shock (not listed in table 3) to be 6.5 and comparing the peak vertical amplitudes of each aftershock with the peak vertical amplitude of the main shock.

Table 3. Aftershocks in the first 7 minutes after the main shock, taken from the Pacoima accelerogram. To obtain origin time, add 14h 00m 44s.

Time m	Time s	Peak amplitude mm.	Relative magnitude
0	30	4.5	5.3
0	40?	0.8	4.4
0	50?	0.8	4.4
0	55	1.0	4.5
1	02	0.8	4.4
1	10	2.0	4.8
1	20	1.0	4.5
1	25	0.5	4.2
1	45	0.5	4.2
1	50	3.0	5.0
2	04	4.0	5.1
2	12	0.5	4.2
2	20	0.5	4.2
2	25	0.5	4.2
2	35	0.5	4.2
2	44	1.5	4.7
2	51	0.5	4.2
2	58	0.3	4.0
3	05	0.8	4.4
3	28	0.5	4.2
3	41	0.8	4.4
3	52	2.5	4.8
3	56	1.0	4.5
4	02	1.5	4.7
4	12	0.5	4.2
4	18	0.3	4.0
4	40	0.3	4.0
4	50	0.6	4.3
5	00	1.0	4.5
5	10	0.5	4.2
5	20	0.8	4.4
5	32	0.8	4.4
5	40	0.5	4.2
6	10	0.5	4.2
6	18	0.5	4.2

A copy of the three-component accelerogram for the aftershock at 14h 02m 48s is given in figure 1. This accelerogram is typical of many of the aftershocks. The interval between the high-frequency onset (15 Hz.) and the longer pulse-like packet (0.8 Hz.) is 1.7 seconds. This time difference is appropriate for a P-wave onset followed by an S-wave packet from a focus at a depth of about 13 km, along the fault plane under the San Gabriel Mountains (see figure 5). This interpretation is supported by the much smaller amplitude of the second packet (S waves) on the vertical component of ground acceleration (central trace in figure 1) compared with the same onset on the horizontal components.

Figure 2 shows a plot of the logarithm of the number (N) of earthquakes in this sequence (given in table 2) with magnitude greater than or equal to M (for $M \geqslant 4.0$). We can represent the relationship between log N and magnitude by a straight line with the equation $\log N = a - bM$ where a and b are constants. Then from figure 2, by least squares, $b = 0.64$, if the main shock is included and 1.01 if the main shock is excluded. When the 35 aftershocks immediately following the main shock listed in table 3 are added, the corresponding b values become 0.78 and 1.16, respectively. The difference may be marginally significant.

The mean value of 'b' for all southern California earthquakes from 1934 to 1963 was found to be 0.86 (Allen *et al.*, 1965). Aftershock sequences were included in the study. These workers found a 'b' value of 1.01 for the Los Angeles Basin. The 'b' value for aftershock sequences is usually less than that for overall seismicity. Udias (1965) obtained a value of 0.49 for the Salinas-Watsonville sequence of August 31, 1963, and 0.41 for the sequence of September 14, 1963.

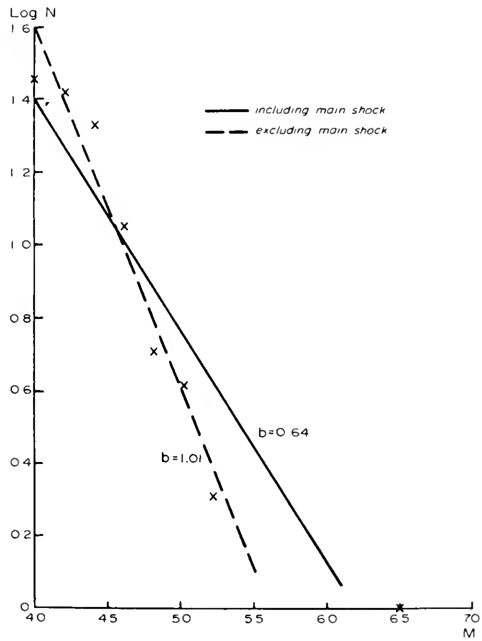


Figure 2. Plot of log N vs. M ($M \geqslant 4.0$). The continuous line is the least squares fit with the main shock included. The dashed line is the fit with the main shock excluded.

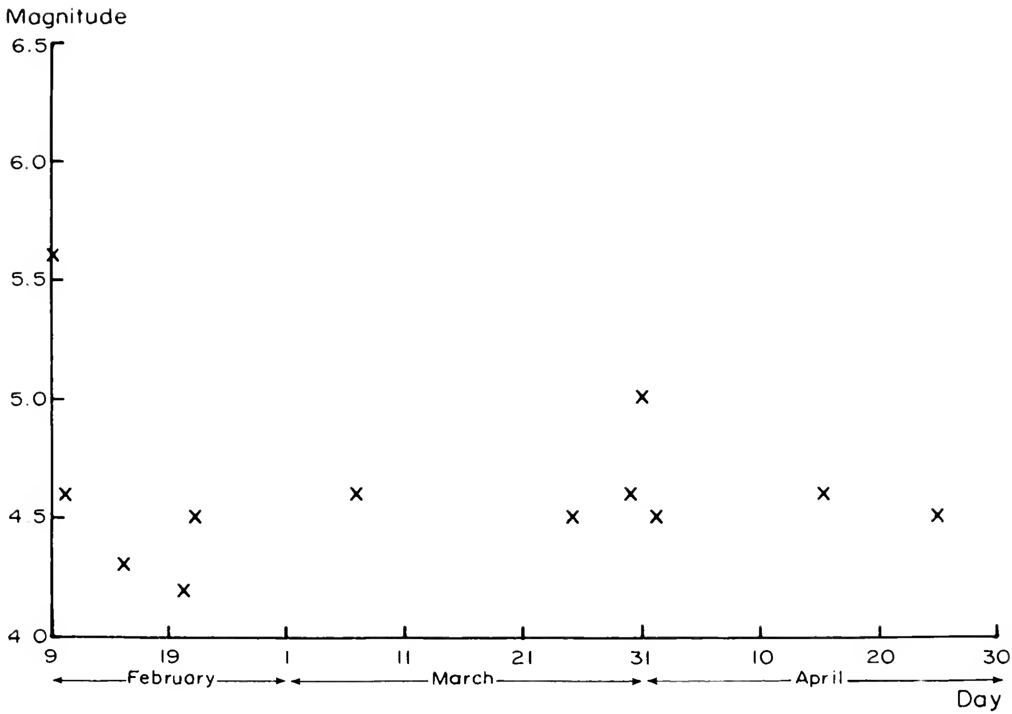


Figure 3. Plot of occurrence (M vs. time) of aftershocks. The magnitude cutoff is 4.0.

McEvilly *et al.* (1967) got a value of 0.63 for the Parkfield sequence of 1966 (main shock included in the three cases).

Lomnitz (1966) pointed out that, in an aftershock sequence, the earthquakes are stable about the mean, but the variance of magnitude tends to be correlated with the rate of occurrence of events; that is, there is a wider scatter of magnitudes at the beginning of the sequence than towards the end. In this case, a plot of M vs. time for $M \geqslant 4.0$ is consistent with the stability of the mean (figure 3).

Figure 4 is the cumulative plot of the occurrence of aftershocks. The magnitude cut-off for these data was 2.8. The plot indicates that it would be October 1971 before the seismicity returns to normal, taken as three earthquakes per month with $M \geqslant 2.8$.

ENERGY AND STRAIN RELEASE OF THE MAIN SHOCK

Assume $\log E = 9.9 + 1.9M_L - .024M_L^2$. The seismic energy released by the main shock is then 1.7×10^{21} ergs. The total energy released by the aftershocks ($M \geqslant 4$) is 4.9×10^{19} ergs. From strain theory,

$$E_{strain} = \tfrac{1}{2} V \mu \varepsilon^2,$$

where V is the volume of the rock where the energy is stored, ε is the average elastic strain, and μ is the modulus of rigidity. Benioff (1965) assumed for the Kern County sequence of 1952 that the surface area of the strain zone was defined by the area covered by the epicenters of the aftershocks and that the depth of the strain zone was 35 km., the thickness of the crust. Here, we assumed that the depth of the strained zone associated with the seismic activity was the depth of the deepest earthquake of the sequence. Wesson *et al.* (1971) have located the aftershocks. The surface area covered by the aftershocks is about 600 sq. km. and the deepest aftershock occurred at a depth of about 15 km, so V is taken to be 9000 km^3 $= 9 \times 10^{18}$ cm^3. Let the efficiency of conversion of elastic energy into seismic energy be $\eta (\eta < 1)$. The elastic strain preceding the main shock is then $\frac{3.8 \times 10^{-5}}{\sqrt{\eta}}$ (taking $\mu = 3 \times 10^{11}$). For an efficiency of $\eta = 0.1$, the crustal strain involved is then about 10^{-4}. The strain calculated by Benioff (1965) for the Kern County earthquake is 5.2×10^{-5}.

STRONG MOTION RECORD

The strong-motion accelerograms from Pacoima Dam (Maley and Cloud, 1971), part of the strong-motion network of the National Ocean Survey, NOAA, were analyzed. The three accelerograms (S

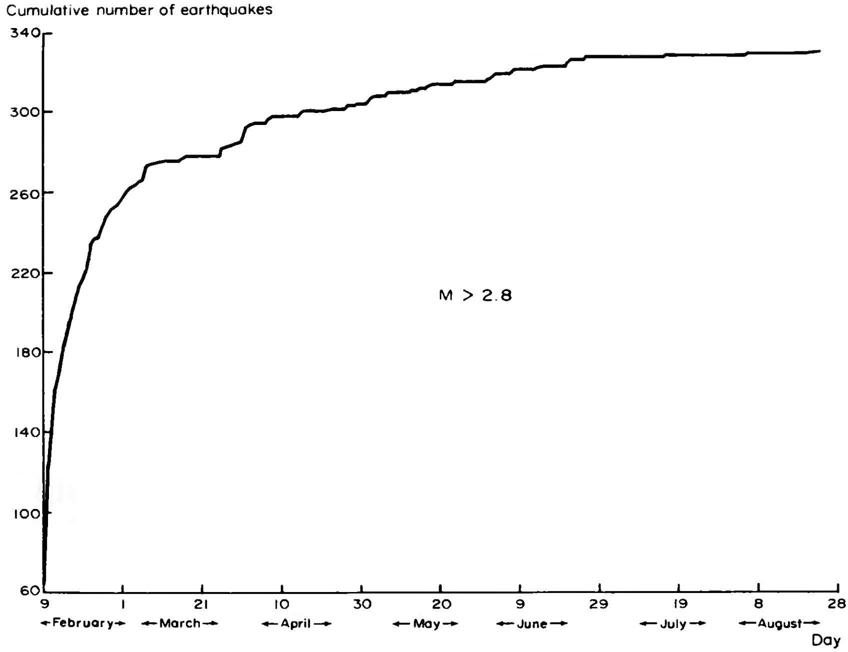


Figure 4. Cumulative plot of occurrence of aftershocks to magnitude 2.8.

74° W, vertical and S 16° E) were resolved into the resultant motions in the direction of the strike of the fault (T), in the downdip direction of the fault (L), and along the normal (N) to the fault plane. The strike of the fault plane was taken to be N 72° W and the dip 55°.

The resolution was done as follows. The digital card deck of the original records, sampled at intervals of .02 second, was converted to continuous analog signal on magnetic tape, using an IBM 1800 computer and a special program. The analog signals were then combined using an analog computer to obtain the three resultants T,L,N. The resolved accelerograms are reproduced in figure 6.

The aim of this vectorial resolution was to disentangle the recorded motion, taking the mechanism of rupture into account.

The transverse component T, on the simple model of predominantly thrust faulting (figure 5), should be relatively small and composed mainly of Love, surface shear, wave motion. In fact, figure 6 shows that the amplitudes of the first 5 seconds of the T record are significantly less than those of the L and N records. Further, the large, relatively long-period pulse (marked S_1) about 1 second after the beginning of L and N is not strong in T. (Some left-lateral fault displacement was observed along the fault rupture.)

On the resolved traces, the maximum acceleration was 0.8 g for L and 1.1 g for N. This large acceleration in the direction normal to the fault plane can be explained on the basis of a double-couple source mechanism (figure 5). When the fault breaks at the focus F, in addition to the sudden fling parallel to the fault plane, this mechanism demands a comparable strong displacement along a plane normal to the fault plane. A similar effect was seen on the Cholame accelerogram (on the component normal to the San Andreas fault) for the 1966 Parkfield earthquake (see Bolt, 1970).

We have made an attempt to explain some of the phases on the resolved accelerograms on the basis of a moving rupture and seismic wave theory applied to a homogeneous elastic half-space (figure 5). Even though the interpretation is oversimplified and speculative because the geologic structure near the source and the detailed dynamics of the rupture are not incorporated, the principal effects should be accounted for.

We assumed that the accelerometer at Pacoima was triggered by the direct P arrival from the focus of the main shock or within about a half second of it. Support for this comes from the following observations: 1) The first wave packet of the aftershocks which continued to be recorded on the Pacoima record appeared very similar in character to the early wave pattern of the main shock. 2) The interval between the first wave arrival and the larger amplitude long-period arrivals (near S_1 in figure 6) was about 1.7 seconds for both the main shock and the aftershocks.

Assume that the dislocation moved from F to T (figure 5) with a velocity of 2.5 km/sec along the fault

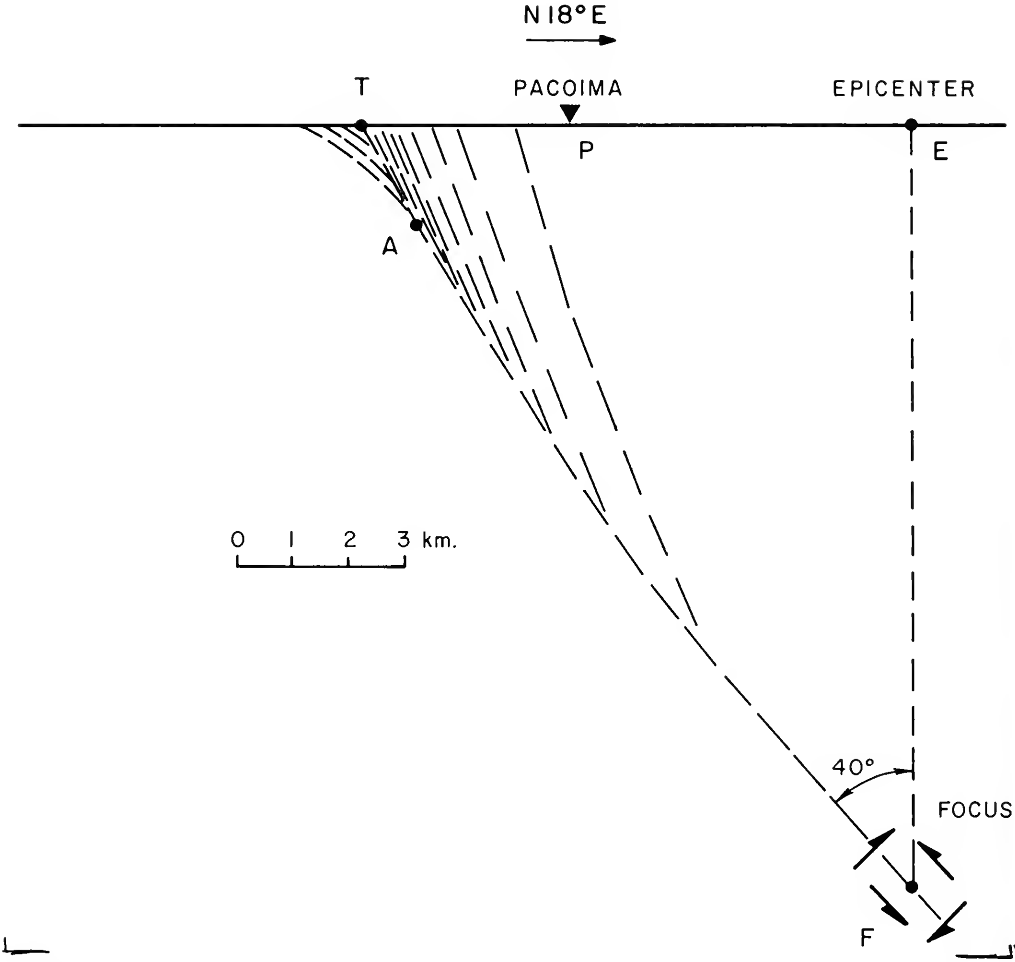


Figure 5. Simple model of the fault. E is the epicenter of the main shock; F is the focus; T is the place where the rupture reached the surface; P is the Pacoima accelerometer site; and A is the point on the fault nearest to P.

and that P and S waves were generated at each point of this moving source. Let the average crustal P velocity be 5.5 km/sec and the S velocity be 3.3 km/sec. Then the first S phase (direct ray path) should arrive at Pacoima about 1.7 seconds after the first P. This theoretical arrival is marked S_1 in figure 6; it coincides with the beginning of the long-period phase on the accelogram. We thus interpret the beginning of the long-period motion as the arrival of the first shear wave by a direct path from the focus.

This inference is supported by the relatively long-period of the phase (1.2 seconds). It is hardly present on the T component, whereas it is pronounced on the L and N components. This suggests that the motion is of the SV type (vertically polarized shear waves). S_2 marked the theoretical arrival time of the SV-pulse from the dislocation source as it moved through the point on the fault (A in figure 5) nearest to Pacoima at a rupture velocity of 2.5 km/sec. By this time, the 1.2-second period acceleration pulse on the record was about complete. The ground displacement has been computed by a double integration of the Pacoima accelerogram by Trifunac and Hudson (1971). This showed that the ground at Pacoima has been displaced by some tens of cms when S_2 arrives. R is the theoretical arrival time of the first Rayleigh surface wave, through basement rock, generated at the point T where the rupture reaches the surface. Because the distances

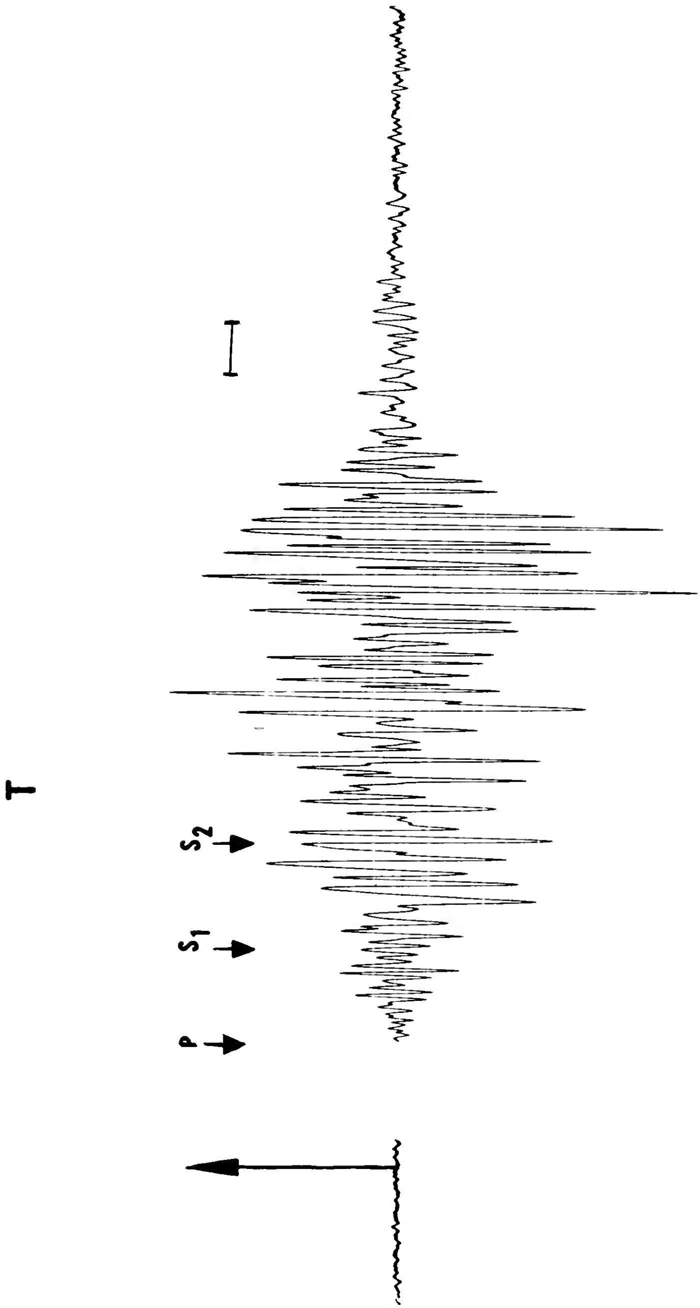


Figure 6a. The resolved accelerogram along the strike of the fault. The length of the line on the top right-hand side of the figure corresponds to 1 second. The distance between the record trace and the vertical arrow tip at the beginning of the record is about 0.5 g. First portion of trace gives a measure of the noise in the analog processing.

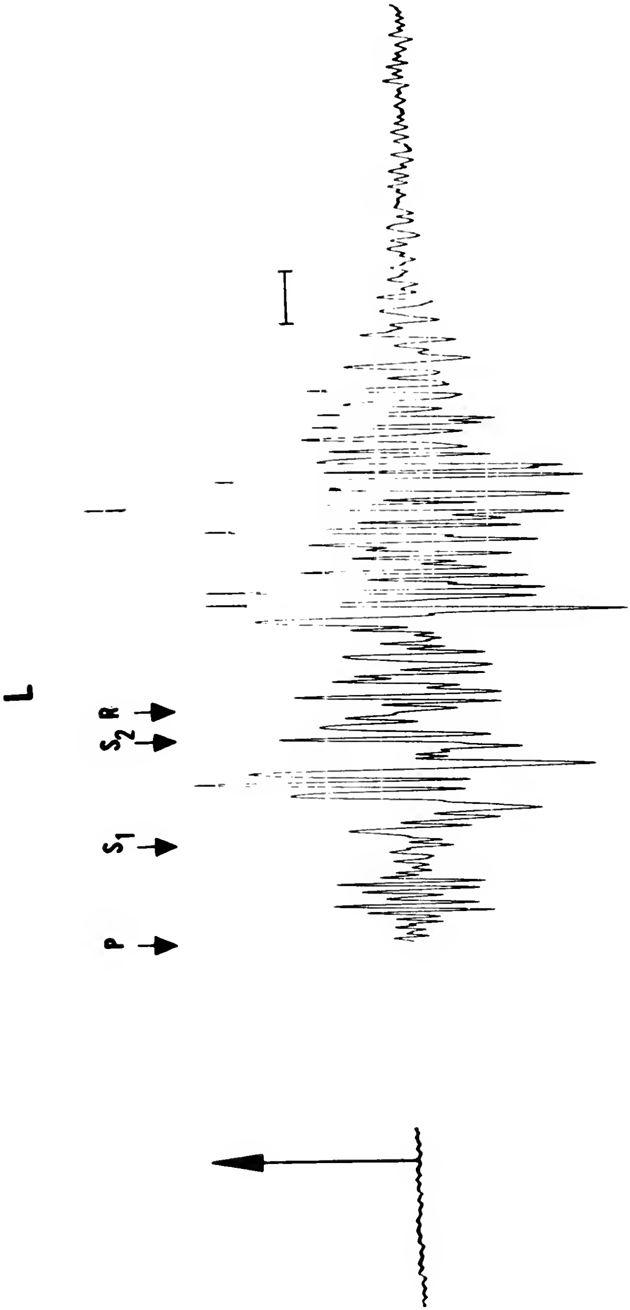


Figure 6b. The resolved accelerogram in the down dip direction.

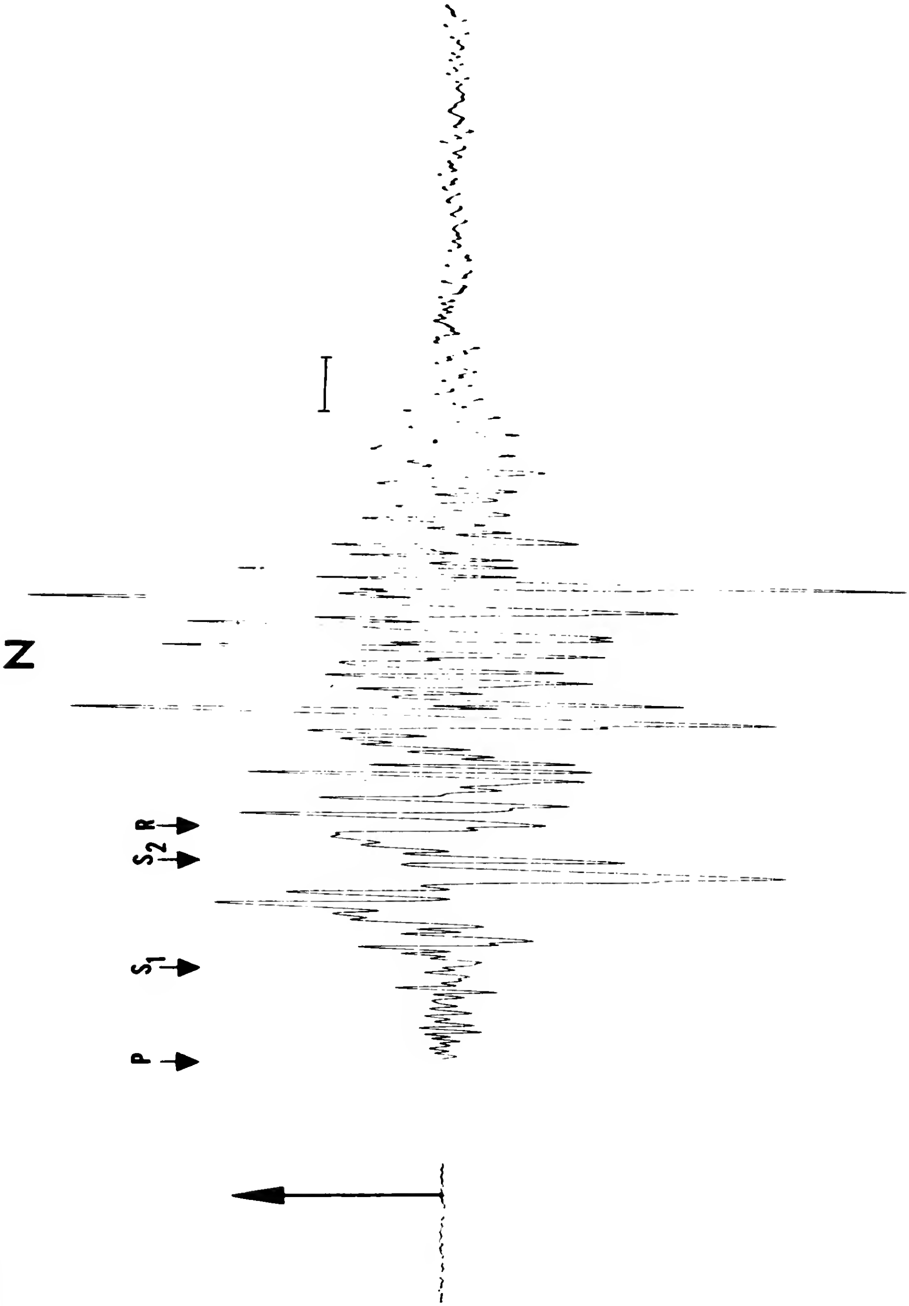


Figure 6c. The resolved accelerogram along the normal to the fault plane.

between Pacoima and the primary wave sources are small, it is doubtful, theoretically, whether Rayleigh waves could contribute significantly to the Pacoima shaking.

The simple two-dimensional model of the source and the crust (without very low velocity surficial layers) adopted above appears able to explain the main features of the first third of the observed accelerogram. The remaining part of the record, which contains large-amplitude high-frequency motion, is still unaccounted for.

Three explanations for the major part of the later shaking might be suggested. First, displacement of the fault in several stages. Because there is only one major step on the Pacoima displacement record, this alternative is unlikely. Secondly, trapped seismic wave propagation in surficial low-velocity material, with scattering, dispersion and mode interference. The strongest high-frequency accelerations in the last half of the record would then be associated with waves traveling as slowly as a few thousand feet per second. These waves would be similar to "ground-roll." However, the Pacoima site is on the crystalline rocks of the San Gabriel mountains which have much higher transmission velocities. Further, this mechanism entails heavy attenuation of high frequencies, contrary to the waves observed.

The third explanation depends on the three-dimensional nature of the fault model (Bolt, 1972). Rupture, no doubt, also spread horizontally from the focus on the dipping fault plane. Fault rupture extending 15 km along the strike from F in figure 5 would reach its horizontal extremity in $15/2.5 = 6$ secs, and the surface (east of Tujunga Canyon) in about $30/2.5 = 12$ secs. During this dislocation, high-frequency S waves would radiate outwards through the crystalline rock to Pacoima with a speed of 3.3 km/sec. In this way, high-frequency little-attenuated waves could continue to arrive at Pacomia for 14 sec after P.

Suppose the fling, 'v,' along the fault behaves like a damped elastic oscillator, with amplitude given by

$$v = D(1 + nt)e^{-nt}/2,$$

where D is the total fault offset and n is the damping constant. Then the absolure maximum acceleration is $n^2 D/2$ initially. From figure 6, the pulse width is about 1.2 seconds, so that $n \approx 1.7$. From the field measurements, $D \approx 2$ meters. Thus, the predicted peak acceleration of the SV pulse is about 0.3 g. The measured acceleration of the 1.2 second pulse (between S_1 and S_2) from the N component of figure 6 is about 0.5 g, in reasonable agreement.

ACKNOWLEDGMENTS

We would like to thank Professor Lane Johnson for comments on the manuscript. The copy of the strong-motion record from Pacoima and a digitized deck of their components were kindly made available by Dr. D. E. Hudson of California Institute of Technology. The Electronic Research Laboratory of the Department of Electrical Engineering and Computer Sciences kindly provided facilities for digital-to-analog conversion.

Revised information in 1973 was that the actual alignment of the Pacoima horizontal instruments was N 76° W, S 14° W. A check showed that the main arguments above are not altered.

Strong Motion Data from the San Fernando, California, Earthquake of February 9, 1971[1]

by William K. Cloud [2] and Donald E. Hudson [3]

The San Fernando, California, earthquake of February 9, 1971, occurred virtually at the center of the largest concentration of strong-motion recording instruments in the United States cooperative network (see Table 1). As a result, an unprecedented amount of valuable data on strong ground and building motion were collected. In fact, more records of engineering significance were obtained during this one earthquake than during the previous 39-year history of the recording program. The benefit to earthquake engineering that eventually will be derived from application of these data will be a highly rewarding payoff for a long-range and patient investment in engineering seismology by the Seismological Field Survey unit of NOAA's Environmental Research Laboratories, in cooperation with numerous institutes, organizations, and individuals.

Table 1. United States cooperative network of strong-motion instruments supervised and maintained by the Seismological Field Survey ERL, NOAA

General location of instruments	Number of strong-motion instruments, 12/31/71	
	Accelerographs	Seismoscopes
Southern California	330	129
Northern California	155	145
Nevada	23	0
Alaska	15	97
Washington	13	5
Central and South America	8	0
Montana	4	0
Arizona	4	4
Oregon	3	1
Colorado	3	0
South Carolina	3	0
Missouri	2	0
Utah	2	0
Tennessee	1	0

The beginning of the program in engineering seismology dates back to the early 1930s when the Coast and Geodetic Survey designed the first strong-motion seismographs and, with the cooperation of engineers, installed a small network of these instruments in California (Cloud, 1964). Responsibility for the network was assigned to the Seismological Field Survey, a newly formed unit of the Coast and Geodetic Survey with headquarters in San Francisco.*

Under supervision of the Seismological Field Survey, the network was gradually expanded but remained small until commercially developed strong-motion accelerographs became available in the early 1960s. Prior to this time, only custom-built instruments originally designed by the Survey could be obtained in limited numbers. Introduction of commercially available strong-motion accelerographs at a modest cost plus the introduction of simplified seismoscopes acted as a stimulus to growth of the network. A further factor in the growth of the network was agreement by the Coast and Geodetic Survey to accept privately owned instruments into the network for maintenance.

The availability of modern instruments and Seismological Field Survey supervision encouraged organizations such as the California Institute of Technology, California Department of Water Resources, U.S. Bureau of Reclamation and the U.S. Corps of Engineers to increase greatly their involvement in the program. Also, individual building owners, subject to provisions of local building codes, found the situation to their advantage. This was especially true in southern California where Los Angeles and Beverly Hills, in 1965, were the first cities in the United States to pass a non-retroactive ordinance requiring building owners to install three accelerographs in buildings of more than six stories. The requirement and its later inclusion in the appendix of the Uniform Building Code was a major

[1] Manuscript submitted for publication January 21, 1972.

[2] Berkeley Seismographic Stations, University of California, Berkeley. (Former Chief, Seismological Field Survey, NOAA.)

[3] Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, California.

* As a result of recent governmental reorganization, the Seismological Field Survey is now a unit of the National Oceanic and Atmospheric Administration's Environmental Research Laboratories.

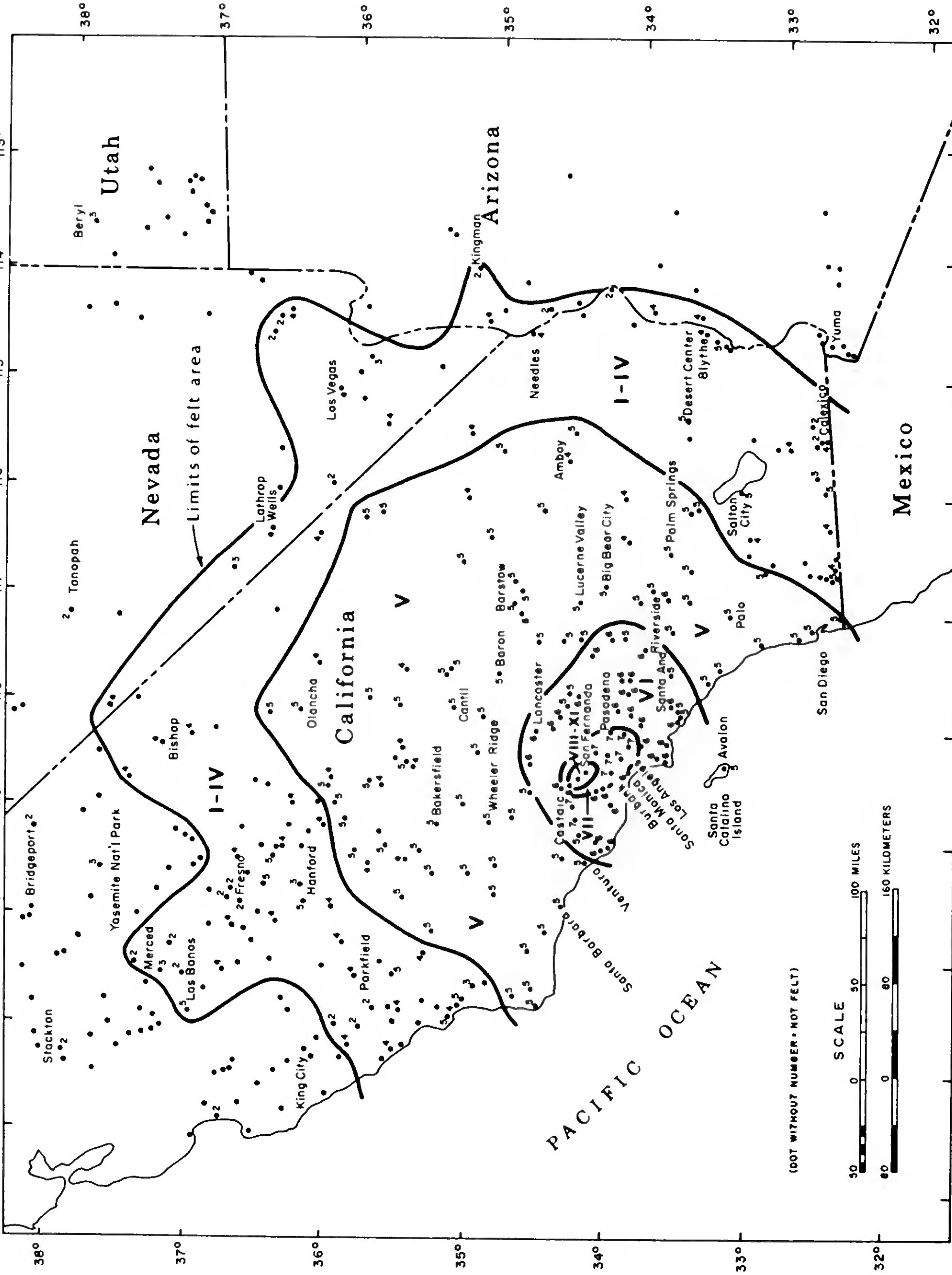


Figure 1. Intensity map of February 9, 1971, San Fernando earthquake.

reason for over half of the accelerographs in the network being concentrated in the area affected by the San Fernando earthquake.

Considering the concentration of instruments (over 200 accelerographs and 140 seismoscopes), it was a fortunate circumstance that prior to the earthquake the Seismological Field Survey ERL, NOAA, and the Earthquake Engineering Research Laboratory, California Institute of Technology, had cooperated closely for years on the engineering seismology program and had worked as a team on previous earthquakes. The combined expertise of the two organizations provided an immediately available, on-site means of handling the large amount of strong-motion data resulting from the earthquake. Efforts of the Seismological Field Survey were directed primarily toward:

(a) Collecting, developing, and labeling records;
(b) Servicing of instruments;
(c) Making preliminary determinations of maximum accelerations;
(d) Processing and analyzing of seismoscope records;
(e) Distributing and collecting questionnaire cards to determine intensity.

While efforts of the Earthquake Engineering Research Laboratory were directed primarily toward:

(a) Production of accurate archival copies of all accelerograms as well as copies suitable for digitization and data processing;
(b) Production of multiple copies suitable for immediate display and distribution to all interested parties;
(c) Accurate digitization of all useable records compatible with past accelerogram analysis;
(d) Presentation of all accelerograms in a standard form, and preparation of corrected accelerograph data, integrated velocity and displacement curves, and various spectra.

INTENSITY DISTRIBUTION

Results obtained from an over 2000 questionnaire card canvass by the Seismological Field Survey supplemented by reports of field investigators indicate that the main shock of the San Fernando earthquake was felt over approximately 80,000 square miles of California, Nevada, and Arizona. A preliminary draft of intensity distribution prepared by Mrs. Nina Scott of the Seismological Field Survey is shown in figure 1.

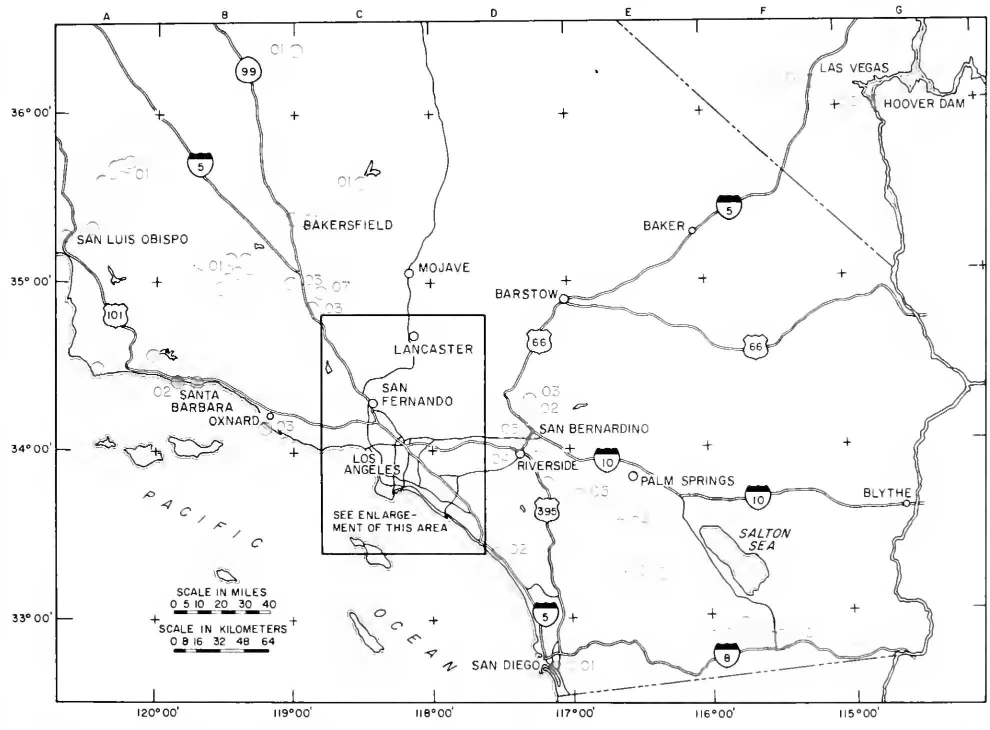


Figure 2. Map of strong-motion accelerograph stations recording the San Fernando earthquake in central and southern California (approximate maximum ground acceleration in fractions of gravity).

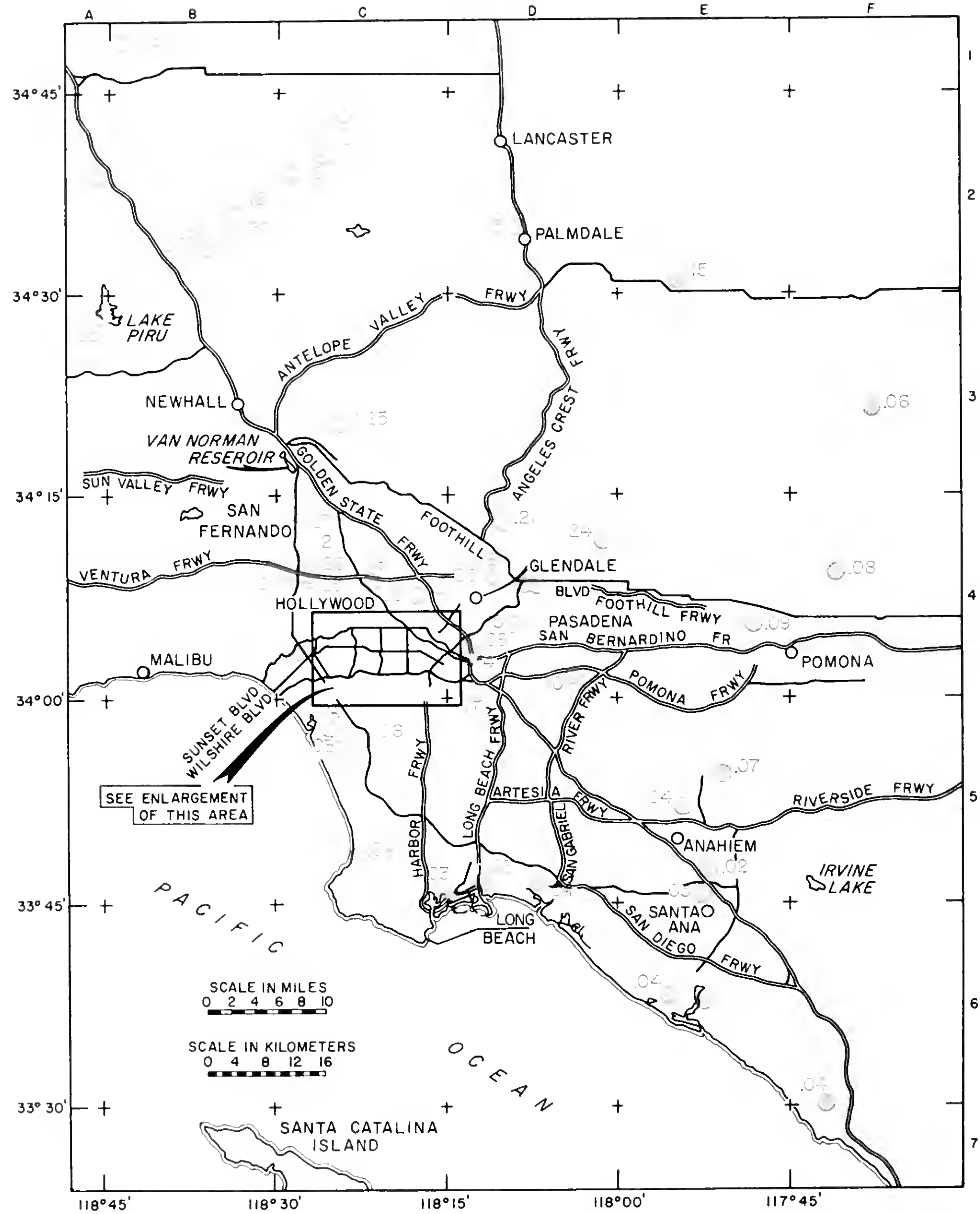


Figure 3. Map of strong-motion accelerograph stations recording the San Fernando earthquake in the extended Los Angeles area (approximate maximum ground acceleration in fractions of gravity).

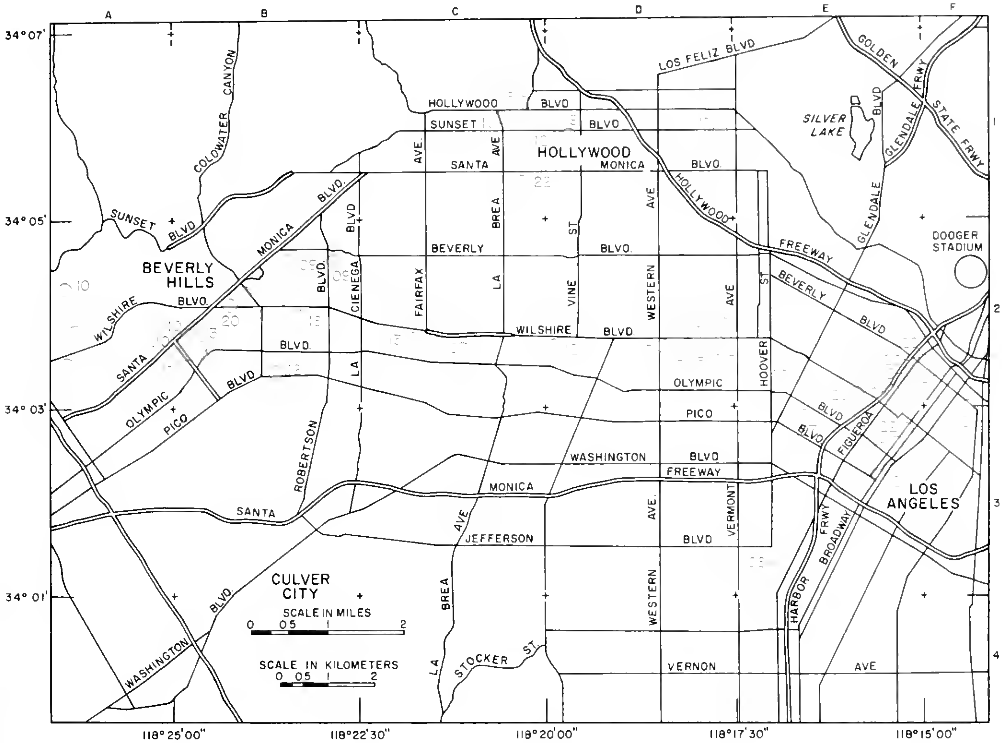


Figure 4. Map of strong-motion accelerograph stations recording the San Fernando earthquake in central Los Angeles area (approximate maximum ground acceleration in fractions of gravity).

Maximum intensity VIII to XI on the Modified Mercalli Scale of 1931 was assigned to the most affected area, the larger value to reflect spotty catastrophic damage such as occurred to the Olive View and other hospitals, to the Sylmar Converter Station, to freeway structures, and to reflect damaging surface ruptures.

STRONG-MOTION ACCELEROGRAPH RECORDS

Two hundred and forty-one accelerograms were recorded during the San Fernando earthquake in the southern California region, making this earthquake by far the best-recorded event in the brief history of strong-motion seismology. When it is considered that many important earthquakes of recent times, such as the great Alaskan earthquake of 1964, did not result in even one record of strong ground motion, the unique value of this unusual wealth of data will become obvious.

The maps of figures 2, 3, and 4 show in successively greater detail the location of the accelerograph stations in the area. At each station, the number indicates the approximate value of the peak ground level acceleration recorded at that site.

A more detailed indication of the peak acceleration results, along with details of the station, will be found in table II, which arranges the stations in order of their distance from the epicenter. In this table, only those stations out to a distance of some 60 km have been included, since the more distant stations have in general progressively smaller motions. Complete data for all stations will be found in Hudson, 1971.

About 175 of the accelerographs were located in large buildings in Los Angeles as the result of an amendment to the building code in 1965, which required three strong-motion accelerographs in all new buildings over six stories in height. About 30 accelerographs were on dams and other hydraulic structures, and an additional 30–40 stations were ground stations, many located along faults or in arrays across the San Andreas fault.

Representative records from three ground sites are shown in figures 5, 6, and 7. A set of three accelerograms from the nearest instrumented tall building to the epicenter (20 km) is shown in figure 8.

Table 2. Maximum accelerations recorded during the San Fernando earthquake of 9 Febraury 1971

Station Name	Identification number*	Location Map	Location Key	Distance from epicenter (km)	Component	Maximum acceleration (g) Ground level	Maximum acceleration (g) Other floors/levels		Geology	Structure type	Comments
1. Pacoima Dam	279	2	C-3	8	Down S 74 W S 16 E	.72 1.25 1.24	----	----	Highly jointed diorite gneiss	Small building	4 kms from surface faulting
2. Los Angeles 8244 Orion	241–3	2	C-4	20	Down North West	.17 .27 .14	*4th* .23 .18 .24	*8-roof* .22 .39 .31	Alluvium	7-story reinforced concrete building	8 kms from surface faulting
3. Los Angeles 15107 Vanowen	458–60	2	C-4	24	Down West South	.12 .11 .12	*4th* .19 .23 .26	*8-roof* .17 .34 .38	Alluvium 500′, watertable at 70′	Circular 7-story reinforced concrete building	13 kms from surface faulting
4. Lake Hughes #12	128	2	B-2	25	Down N 21 E N 69 W	.18 .37 .28	----	----	Eocene sandstone below a shallow (10′±) layer of alluvium	Small building	
5. Los Angeles 14724 Ventura	253–5	2	C-4	28	Up N 78 W S 12 W	.09 .19 .26	*6th* .11 .27 .36	*13-roof* NR .21 .32	Alluvium	12-story reinforced concrete building	
6. Los Angeles 15250 Ventura	466–8	2	C-4	28	Down S 09 W S 81 E	.10 .23 .14	*7th* .18 .25 .21	*13-roof* .13 .26 .18	Alluvium, water table at 55′	12-story reinforced concrete building	
7. Los Angeles 15433 Ventura	256–8	2	C-4	28	Up N 12 E N 78 W	NR NR NR	*7th* .15 .24 .17	*13th* .07 .27 .23	Alluvium	13-story reinforced concrete building	
8. Los Angeles 15910 Ventura	461–3	2	C-4	28	Down S 09 W S 81 E	.11 .13 .15	*9th* .22 .18 .13	*18-roof* .21 .22 .23	Alluvium, water table at 35′	17-story steel building.	
9. Los Angeles 16055 Ventura	259–61	2	C-4	28	--------	NR	NR	NR	35′ of alluvium over siltstone and sandstone, water table at 50′	12-story reinforced concrete building	Mid-level accelerograph out for repair
10. Los Angeles 16661 Ventura	118–20	2	C-4	28	--------	----	----	----	Alluvium	9-story reinforced concrete building	Owner did not supply batteries

11. Pasadena J P L	267–8	2	D-4	29	Down S 08 W S 82 E	.13 .17 .21	*10-roof* .26 .21 .38	Sandy gravel	9-story steel building	
12. Lake Hughes #4	126	2	C-2	29	Down S 21 W S 69 E	.16 .16 .19	---- ----	Weathered granitic	Small building	
13. Lake Hughes #9	127	2	B-2	29	Down N 21 E N 69 W	.12 .15 .16	---- ----	Gneiss	Small building	
14. Castaic	110	2	B-2	29	Down N 21 E N 69 W	.18 .39 .32	---- ----	Sandstone	Small building	
15. Los Angeles 3838 Lankershim	220–2	2	C-4	30	Down North West	.09 .18 .13	*11th* *20th* PR .23 PR .10 PR .21	Interlayered soft sandstone and shale	20-story reinforced concrete building	
16. Lake Hughes #1	125	2	C-2	31	Down N 21 E N 69 W	.12 .17 .13	---- ----	Granitic	Small building	
17. Glendale 633 E. Broadway	122	2	D-4	32	Down S 70 E S 20 W	.14 .28 .23	---- ----	Alluvium	3-story building	
18. Los Angeles Griffith Park Observatory	141	2	C-4	33	Down South West	.12 .18 .16	---- ----	Granitic	Concrete pier on bed rock	
19. Palmdale	262	2	D-2	33	Down S 60 E S 30 W	.08 .11 .13	---- ----	Alluvium	Small building	
20. Santa Felicia Dam	284–5	2	A-3	33	Down S 82 W S 08 E	*Abutment* .09 .24 .23	*Crest* ---- ----	Sandstone-shale complex	Earth-fill dam. Height 200′, crest length 1260′	6 seismoscope records also obtained on and near the dam.
					Down S 75 W S 15 E	---- ---- ----	.07 .18 .22			
21. Pasadena Seismological Laboratory	266	2	D-4	34	Down South East	.08 .19 .11	---- ----	Weathered granitic	2-story building	
22. Los Angeles 7080 Hollywood	238–40	3	C-1	34	Down East North	.06 .11 .10	*6th* *12-roof* .16 .22 .19 .21 .12 .12	Alluvium	11-story reinforced concrete building	
23. Los Angeles 1760 N. Orchid	446–8	3	C-1	34	Up South East	.08 .16 .13	*12th* *22nd* .14 .19 .08 .11 .14 .20	Alluvium	22-story reinforced concrete building	

Table 2 (continued)

Station Name	Identification number*	Location Map	Location Key	Distance from epicenter (km)	Component	Maximum acceleration (g) Ground level	Maximum acceleration (g) Other floors/levels		Geology	Structure type	Comments
24. Los Angeles 6430 Sunset	232-4	3	D-1	34	Up South East	.09 .19 .14	*7th* NR NR NR	*14th* NR NR NR	Alluvium, water table at 55′	14-story steel building	
25. Los Angeles 6464 Sunset	235-7	3	D-1	34	Up South East	.08 .11 .12	*6th* PR PR PR	*12-roof* .29 .24 .28	Alluvium, water table at 55′	11-story steel building	
26. Los Angeles Hollywood Storage	133-5	3	C-1	35	Up East South	*P.E. Lot-Base* .12 .22 .19	.06 .15 .11	*Roof* NR NR NR	700′± of alluvium	14-story reinforced concrete building	
27. Los Angeles 4867 Sunset	226-8	3	D-1	35	Down S 89 W S 01 E	.13 .17 .17	*3rd level* .13 .30 .22	*8th level* .20 .45 .46	Shallow alluvium over Miocene siltstone	8-story reinforced concrete building	Accelerographs on B and 2 in north wing, on 7 in east wing.
28. Fairmont Reservoir	121	2	C-2	36	Up N 34 W N 56 E	.05 .10 .07	----	----	Granitic		
29. Beverly Hills 435 N. Oakhurst	452-4	2	C-2	36	Down North West	.04 .06 .09	*5th* .05 .13 .14	*11-roof* .10 .24 .25	Alluvium, water table at 22′	10-story reinforced concrete building	
30. Los Angeles 120 Robertson	142-4	3	B-2	36	Down S 02 W S 88 E	.03 .09 .09	*4th* NR .18 .18	*9th* .12 .33 .28	Alluvium	9-story reinforced concrete building	
31. Beverly Hills 450 N. Roxbury	455-7	3	B-2	37	Down N 50 E N 40 W	.04 .20 .17	*5th* .10 .22 .21	*10th* .12 .30 .22	Alluvium	10-story reinforced concrete building	
32. Beverly Hills 9100 Wilshire	416-8	3	B-2	37	Up East South	.04 .16 .12	*5th* .08 .13 .15	*11-roof* PR PR PR	Alluvium, water table at 40′	10-story reinforced concrete building	
33. Beverly Hills 9450 Wilshire	434-6	3	B-2	37	--------	NR	NR	NR	Alluvium, water table at 40′+	10-story reinforced concrete building	

34. Los Angeles UCLA	140	3	A-2	37	Up North West	.07 .10 .09	----	----	70′ of alluvium over 5000′ of sedimentary rock	7-story building	Instrument adjacent to UCLA reactor
35. Pasadena CIT Athenaeum	475	2	D-4	37	Down East North	.10 .11 .10	----	----	Approximately 1000′ of alluvium upon granite	2-story building	
36. Pasadena Millikan Library CIT	264–5	2	D-4	37	Down East North	.12 .18 .22	*10-roof* .14 .34 .33		Approximately 1000′ of alluvium upon granite	9-story reinforced concrete building	
37. Century City Ground Station	410	3	B-2	38	--------	NR	----	----	Alluvium	Small building	
38. Los Angeles 1900 Avenue of Stars	184–6	3	B-2	38	Up S 46 E N 44 E	.06 .08 .10	*16th* PR PR PR	*28-roof* .35 .15 .12	Silt and sand layers. Water level at 70′	27-story steel building	
39. Los Angeles 1901 Avenue of Stars	187–9	3	B-2	38	Down N 46 W S 44 W	.07 .12 .17	*9th* .14 .18 .11	*21-roof* PR PR PR	Silt and sand layers. Water table at 70–80′	19-story steel building	
40. Los Angeles 1800 Century Park East	425–7	3	B-2	38	Down S 36 E N 54 E	.08 .08 .10	*5th* .16 .21 .22	*16-roof* .31 .28 .28	Silt and sand layers. Water table at 70–80′	15-story reinforced concrete building	
41. Los Angeles 1880 Century Park East	440–2	3	B-2	38	Down N 54 E N 36 W	.07 .11 .13	*7th* .12 .10 .14	*17-roof* .27 .10 .12	Silt and sand layers. Water table at 70–80′	16-story steel building	
42. Los Angeles 1888 Century Park East Bldg.	419–21	3	B-2	38	Down N 54 E N 36 W	NR NR NR	*14th* .19 .14 .06	*20th* .35 .15 .08	Silt and sand layers. Water table at 70–80′	20-story steel building	
43. Los Angeles 1888 Century Park East—Ramp	422–4	3	B-2	38	Down S 36 E N 54 E	NR NR NR	*Level 5* .09 .18 .12	*Level 9* .11 .38 .31	Silt and sand layers. Water table at 70–80′	6-story (9 levels) reinforced concrete parking ramp	Basement accelerograph out for repair
44. Los Angeles 2080 Century Park East	193–5	3	B-2	38	Up N 50 E N 40 W	NR NR NR	*10th* NR NR NR	*19-roof* .23 .35 .18	Alluvium	17-story reinforced concrete building	
45. Los Angeles 930 Hilgard	407–9	3	A-2	38	Up N 76 W N 14 E	PR PR PR	*8th* PR PR PR	*15th* .16 .15 .20	Alluvium, water level at 55′	15-story reinforced concrete building	Upper 2 instruments in elevator tower structurally separated from the north and south residential towers

Table 2 (continued)

Station Name	Identification number*	Location Map	Location Key	Distance from epicenter (km)	Component	Maximum acceleration (g) Ground level	Other floors/levels		Geology	Structure type	Comments
46. Los Angeles 945 Tiverton	178–80	3	A-2	38	Down N 78 W S 12 W	NR NR NR	*8th* .10 .12 .23	*14th* .15 .14 .18	Alluvium	14-story reinforced concrete building	
47. Los Angeles 4680 Wilshire	223–5	3	D-2	38	Down N 15 E N 75 W	.08 .12 .09	*3rd* .13 .22 .18	*6th* .16 .24 .30	Alluvium	7-story reinforced concrete building	
48. Los Angeles 5900 Wilshire	428–30	3	C-2	38	Up N 83 W S 07 W	.03 .07 .07	*16th* .08 .12 .10	*33-roof* .15 .17 .14	Alluvium—asphaltic sands	31-story steel building	
49. Los Angeles 6200 Wilshire	443–5	3	C-2	38	Up N 08 E N 82 W	.04 .13 .13	*10th* .07 .28 .15	*17th* .07 .30 .26	Thin layer of alluvium over asphaltic sands	17-story reinforced concrete building	
50. Los Angeles 1177 Beverly Dr.	413–5	3	B-2	39	Up N 31 W N 59 E	.07 .12 .11	*3rd* NR NR NR	*7th* NR NR NR	Alluvium	Arcuate shaped 7-story reinforced concrete building	Accelerograph on 7 was out for repair
51. Los Angeles 616 S. Normandie	431–3	3	D-2	39	Down North West	.05 .10 .11	*8th* .10 .22 .14	*17-roof* .20 .31 .23	Alluvium. Siltstone at 25′	17-story reinforced concrete building	
52. Los Angeles 3407 W. Sixth	199–201	3	D-2	39	Down South East	.06 .17 .19	*4th* .10 .21 .21	*8-roof* .26 .29 .21	Alluvium	7 stories, 2 steel and 5 reinforced concrete	
53. Los Angeles 3345 Wilshire	196–8	3	D-2	39	Down South East	.07 .12 .09	*2nd* NR .17 .11	*12th* .12 .21 .26	Alluvium	12-story reinforced concrete building	
54. Los Angeles 3411 Wilshire	202–4	3	D-2	39	Up South West	.07 .11 .14	*13th* PR PR PR	*31st* PR PR PR	Siltstone. Water table at basement level	31-story steel building	
55. Los Angeles 3470 Wilshire	208–10	3	D-2	39	Down East North	.05 .12 .15	*5th* .10 .24 .21	*11th* .16 .22 .23	Alluvium	11-story reinforced concrete building	

56. Los Angeles 3550 Wilshire	211–3	3	D-2	39	Up North West	.06 .18 .12	*11th* NR NR NR	*21st* NR NR NR	Alluvium, water table at 35′	21-story steel building	
57. Los Angeles 3710 Wilshire	217–9	3	D-2	39	Down West South	.08 .17 .16	*5th* .10 .27 .16	*11th* .17 .37 .22	Alluvium	11-story reinforced concrete building	
58. Los Angeles 2500 Wilshire	449–51	3	E-2	40	Down N 29 E N 61 W	.04 .10 .10	*8th* .07 .13 .16	*14-roof* .14 .20 .19	Alluvium. Siltstone at 20–30′. Water table at 35′	13-story reinforced concrete building	
59. Los Angeles Water & Power	137–9	3	F-2	41	Down N 50 W S 40 W	.08 .14 .20	*7th* .10 .17 .13	*15th* .17 .16 .12	Miocene siltstone	15-story steel building	
60. Los Angeles 222 S. Figueroa	145–7	3	E-2	41	Up N 53 W S 37 W	.04 .15 .12	*12th* PR PR PR	*18-roof* .09 .40 .31	25′ of alluvium over shale. Water at 20′	17-story reinforced concrete building	Instruments in different building sections, G—north tower and 20—south tower.
61. Los Angeles 234 S. Figueroa	148–50	3	E-2	41	Up S 53 E N 37 E	.06 .17 .20	*12th* NR NR NR	*18-roof* .17 .50 .44	25′ of alluvium over shale. Water at 20′	17-story reinforced concrete building	Instruments in different sections. G—west tower, 12—elevator tower and 20—east tower.
62. Los Angeles 445 S. Figueroa	157–9	3	E-2	41	Down N 52 W S 38 W	.06 .14 .13	*19th* .12 .21 .13	*39th* NR NR NR	Shale	39-story steel building	
63. Los Angeles 250 E. First	151–3	3	F-2	41	Down N 36 E N 54 W	.04 .09 .13	*8th* .07 .21 .17	*17-roof* .21 .16 .18	Alluvium	15-story steel building	
64. Los Angeles 800 W. First	172–4	3	E-2	41	Up N 53 W N 37 E	.06 .15 .09	*16th* .15 .18 .11	*32-roof* .22 .28 .18	Pliocene siltstone	31-story steel building	
65. Los Angeles 533 S. Fremont	160–2	3	E-2	41	Up N 30 W S 60 W	.08 .25 .22	*6th* .16 .34 .31	*11-roof* PR PR PR	Alluvium	10-story reinforced concrete building	
66. Los Angeles 750 S. Garland	169–71	3	E-2	41	Down S 30 W N 60 W	PR PR PR	*2nd* .10 .22 .16	*8th* .15 .30 .23	Alluvium	8-story reinforced concrete building	

Table 2 (continued)

Station Name	Identification number*	Location Map	Location Key	Distance from epicenter (km)	Component	Maximum acceleration (g) Ground level	Maximum acceleration (g) Other floors/levels		Geology	Structure type	Comments
67. Los Angeles 420 S. Grand	154–6	3	E-2	41	Down S 37 W S 53 E	*2nd* .07 .12 .17	*10th* PR PR PR	*17th* .23 .23 .32	Shale and siltstone—several 1000′	16-story steel building. Note comment	Second floor is ground level. Floor numbers from adjoining building.
68. Los Angeles 1625 Olympic	469–71	3	E-3	41	Down N 28 E N 62 W	.16 .14 .27	*6th* .14 .18 .22	*10th* .24 .23 .28	Alluvium	10-story reinforced concrete building	
69. Los Angeles 611 W. Sixth	163–5	3	E-3	41	Down N 52 W N 38 E	.06 .10 .11	*24th* NR NR NR	*43rd* .11 .11 .18	Alluvium	43-story steel building	
70. Santa Anita Dam	104	2	D-4	42	Down N 03 E N 87 W	.07 .18 .24	----	----	Granite diorite complex	Small building	
71. Alhambra 900 S. Fremont	482–4	2	D-4	42	Down West South	.09 .13 .11	*6th* .11 .15 .14	*12th* .17 .18 .15	Few 100 feet of alluvium over siltstone	12-story steel building	
72. Los Angeles 1150 S. Hill	437–9	3	E-3	42	Down S 53 E N 37 E	.05 .12 .09	*5th* .09 .11 .10	*10th* .15 .14 .11	500′ of gravely sand over shale	10-story steel building	
73. Los Angeles 3663 Hoover	214–6	3	E-3	42	--------	NR	NR	NR	400′ of alluvium	7-story reinforced concrete building	
74. Los Angeles 646 S. Olive	166–8	3	E-3	42	Down S 37 W S 53 W	.08 .22 .25	*4th lev.* .12 .25 .26	*7th lev.* .26 .38 .48	Ailuvium	8 level reinforced concrete parking ramp	
75. Los Angeles 808 S. Olive	175–7	3	E-3	42	Down S 37 W S 53 E	.09 .14 .13	*4th lev.* .19 .16 .26	*8th lev.* .24 .25 .44	Alluvium	8 level reinforced concrete parking ramp	
76. Los Angeles 1640 Morengo	181–3	2	D-4	42	Down N 38 W S 52 W	.08 .14 .14	*4th* .12 .20 .26	*8-roof* .13 .24 .44	Pleistocene alluvium. Water level at 35′	7-story reinforced concrete building	

77. Los Angeles 11661 San Vicente	250–2	2	C-4	42	Up N 35 W S 55 W	NR NR NR	*5th* .11 .08 .09	*11-roof* .16 .10 .11	Alluvium. Water table at 57′	10-story reinforced concrete building	
78. Los Angeles 3440 University U S C	205–7	3	E-3	42	Up S 61 E N 29 E	.05 .08 .06	*5th* .08 .13 .14	*13-roof* .09 .24 .26	400′ of alluvium over clay and shale. Water table at 275′	12-story reinforced concrete building	Roof accelerograph is in top of small elevated penthouse.
79. Los Angeles 2011 Zonal	190–2	2	D-4	42	Down S 28 W S 62 E	.06 .08 .07	*5th* .08 .16 .18	*9th* .12 .20 .21	Shale at east end of building. 8′ of fill at west end	9-story reinforced concrete building	
80. Pyramid	58	2	A-2	44	--------	NR	----	----	Shale	Small building	
81. Pearblossom	269	2	E-2	46	Down North West	.06 .10 .15	----	----	400′ of alluvium over 14,000′ of sedimentary rock	Small building	
82. Vernon	288	2	D-4	46	Up S 07 W N 83 W	.05 .09 .11	----	----	>1000′ of alluvium. Water table >300′	6-story building	
83. Los Angeles 8639 Lincoln	244–6	2	C-5	48	Down S 45 W S 45 E	.04 .04 .04	*6th* .05 .10 .10	*12th* .06 .12 .12	Terrace deposits—sand	12-story reinforced concrete building	
84. Los Angeles 9841 Airport Blvd.	247–9	2	C-5	49	Up North West	.01 .03 .03	*7th* NR NR NR	*14th* .05 .10 .09	Alluvium	14-story reinforced concrete building	
85. Los Angeles 5260 Century	229–31	2	C-5	49	Up East North	.02 .06 .06	*4th* .04 .04 .07	*8-roof* .08 .09 .06	Alluvium	7-story steel building	
86. Whittier Narrows Dam	289	2	D-4	52	Down S 53 W S 37 E	.05 .10 .10	----	----	More than 100′ of alluvium	Earth-fill dam. Height 56′, crest length 14,960′	
87. Oso Pump Plant	52	2	B-1	55	Down North West	.06 .05 .05	----	----	Alluvium	Small building	
88. Puddingstone Dam	278	2	E-4	62	Down N 55 E N 35 W	.05 .09 .05	----	----	Volcanic clastics and intrusions with associated shales	Small building	
89. Palos Verdes Estates	411	2	C-5	67	Down S 25 E N 65 E	.01 .04 .02	----	----	Shallow Pleistocene sands over shale—volcanic complex	2-story building	

* Refers to list in "Strong-Motion Instruments Data" table annually issued by the Seismological Field Survey.
Abbreviations: PR = partial record; NR = no record.

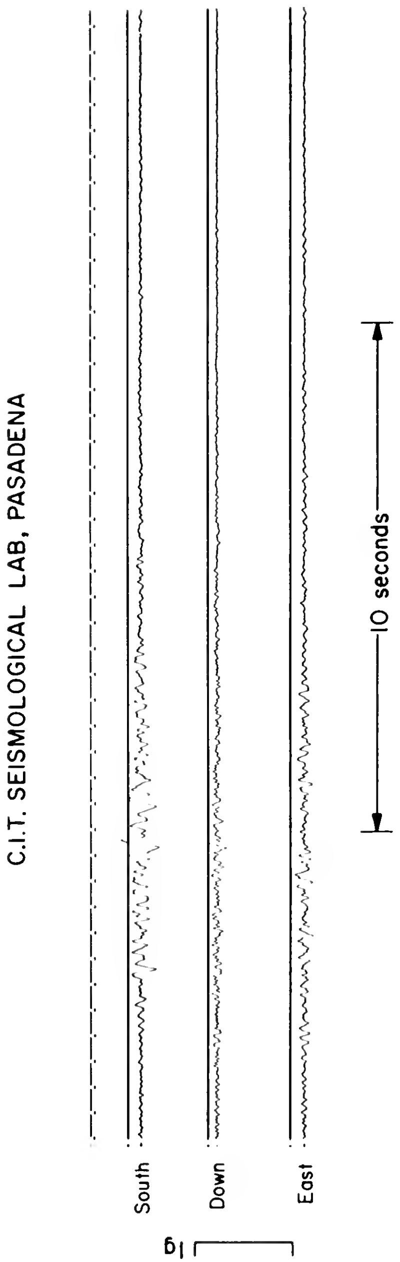


Figure 5. RFT-250 accelerograph record from CIT Seismological Laboratory, Pasadena, 34 km from epicenter.

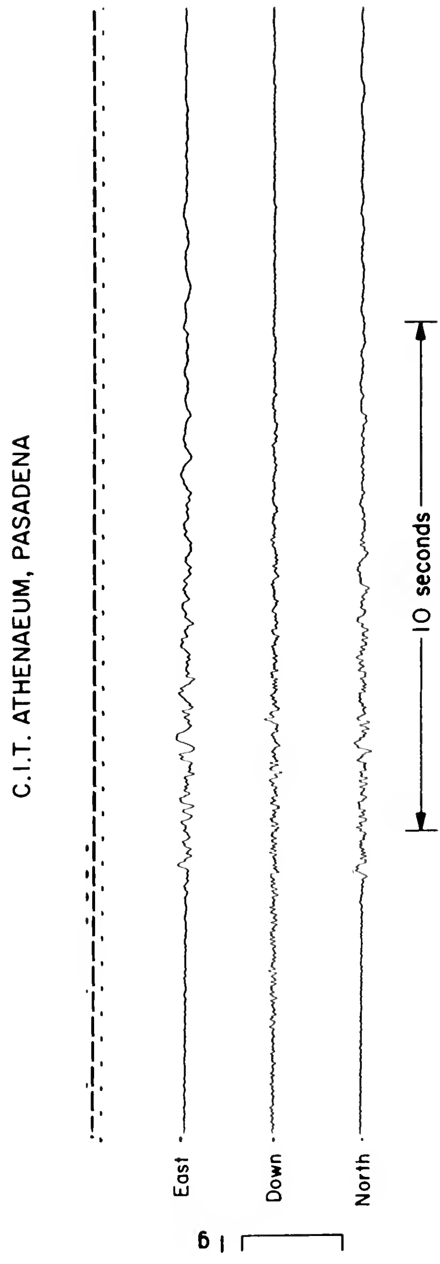


Figure 6. SMA-1 accelerograph record from CIT Athenaeum, Pasadena, 37 km from epicenter.

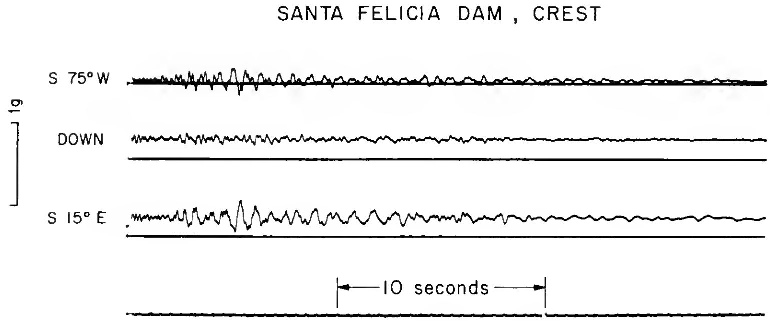


Figure 7. AR-240 accelerograph record from crest of Santa Felicia Dam, 33 km from epicenter.

MAXIMUM ACCELERATION

Included among the records obtained was the notable accelerogram from Pacoima Dam, located virtually at the center of the epicentral region, as shown in figure 9. This record, one horizontal component of which is shown in computer plotted form in figure 10, showed relatively high-frequency peak accelerations as large as 1.25 gm. These peak values are larger by a factor of two than measured before during an earthquake. It must be kept in mind, however, that peak acceleration values alone do not correlate with damage to structures and that duration and frequency content are also important factors. Although the accelerogram recorded at Pacoima Dam is undoubtedly that of very strong ground motion, it is for some structures not the most destructive type of motion that has been measured (Housner, 1970).

Because of the importance of the Pacoima Dam record and of the rather special conditions at the site, a brief description of the installation will be given (Trifunac and Hudson, 1971): The accelerograph is mounted on a concrete foundation firmly attached to a small gneissic granitic ridge adjacent to and above one abutment of the concrete arch dam. This jointed and fractured ridge was severely affected by the earthquake, as evidenced by extensive cracks in the gunite coating, many of which penetrate into the rock below. A small rock slide occurred some 15 feet from the accelerograph but fortunately was not large enough to disturb the accelerograph foundation. After the earthquake, the instrument mounting pier was still solidly attached to the foundation rock, and the mounting bolts attaching the accelerograph to the pier were tight and undisturbed. Although some cracks were observed near the instrument house, apparently none of them penetrated to the base of the accelerograph pier. The only sign of permanent disturbance was a small permanent tilt of the instrument during the earthquake, which could be estimated to be of the order of half a degree. This tilt was just sufficient to close the electrical contacts on the horizontal starting pendulum so that the accelerograph continued running after the main shock for some 6 minutes until the supply of photographic paper was exhausted. During this interval, at least 30 aftershocks were recorded, and in this sense the small permanent tilt of the rock may be considered as a fortunate accident. In no other case has such an exact sequence of initial aftershock been recorded in the epicentral region.

After the earthquake, complete tests made on the accelerograph showed that the instrument was functioning correctly and that there were no significant disturbances to the mechanism. The peak acceleration values remained on scale on the photographic paper, and there is no evidence of an appreciable nonlinear response at the maximum amplitudes involved. The quality of the photographic trace was excellent and permitted an accurate and complete digitization.

There is no reason to doubt that the accelerograph at the Pacoima Dam site accurately recorded the true motions of its foundation pier. A question may be asked, however, as to the relationship between the accelerations on the particular ridge under unusually complex conditions of local geology and the whole pattern of acceleration measured in the region. How the peak accelerations at Pacoima Dam should be expected to compare with values at the caretaker's house below the dam, where little damage occurred, or at the nearby Olive View Hospital, where major damage occurred, are questions which cannot be answered in the present state of the art. It seems likely that details of local topography and geology may influence such peak values in a major way; but, until many more measurements are made, there can be no definite conclusions for specific cases.

Except for the maximum acceleration recorded at the Pacoima Dam station, maximum accelerations recorded at strong-motion ground level stations during the San Fernando earthquake were not unusual in comparison with maximum accelerations recorded at various distances from epicenters during other earthquakes. As figure 11 indicates, the attenuation of maximum acceleration with distance from epicenter, with the one exception, agrees reasonably well with the superimposed curves developed by Cloud and Perez (1970) using data shown in figure 12. Note in figure 12 that,

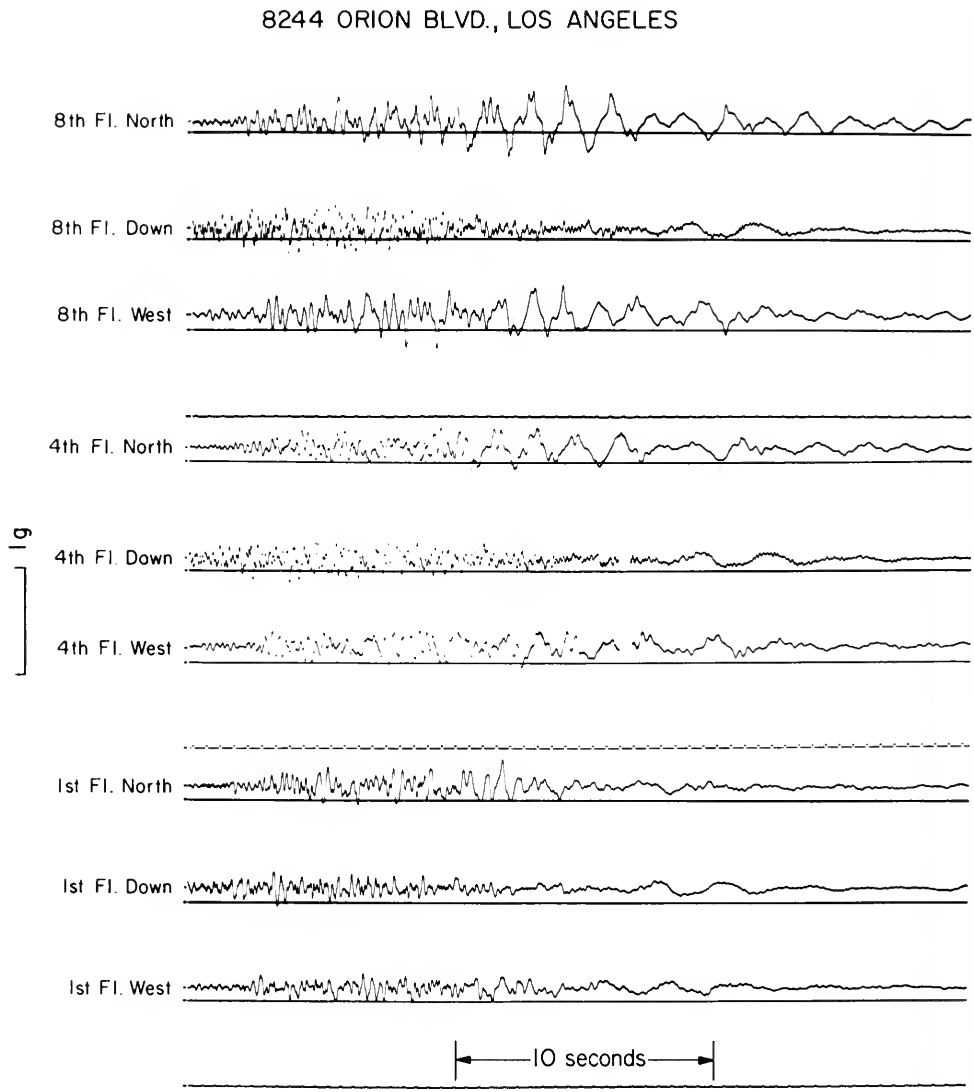


Figure 8. AR-240 acceleragraph records from three instruments at 8244 Orion St., 20 km from epicenter.

while the curves represent reasonable envelopes for the bulk of the data, there are more exceptions than Pacoima. Whether or not such exceptions are of important engineering concern is a matter requiring more study.

DIGITIZATION AND ANALYSIS OF DATA

During the past several years a considerable amount of experience has been gained at the Earthquake Engineering Research Laboratory of the California Institute

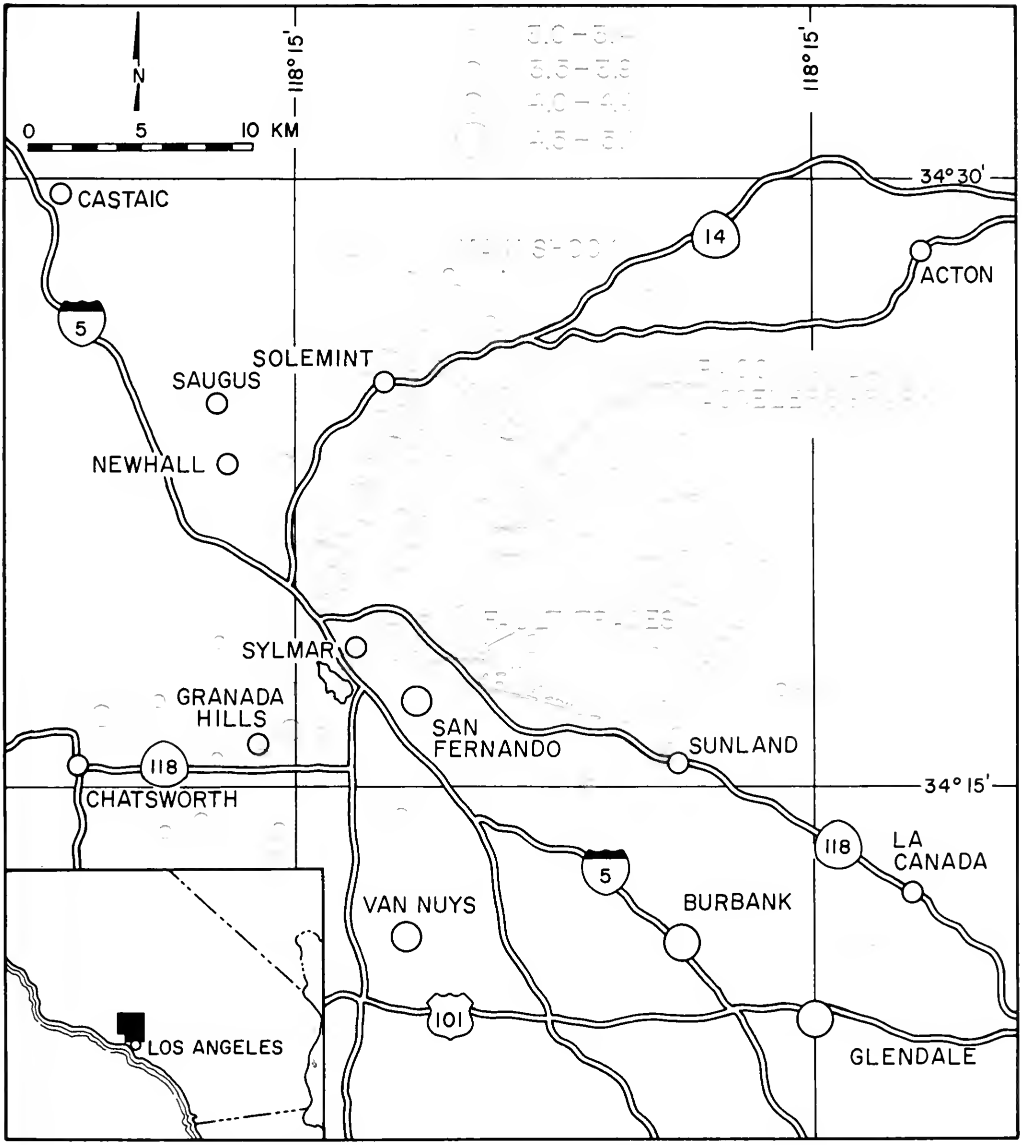


Figure 9. Map of epicenters of main shock and representative aftershocks showing location of Pacoima Dam accelerograph.

of Technology on the digitization of strong-motion accelerograms on a Benson-Lehner 099D Datareducer (Hudson and Brady, 1967; Brady and Hudson, 1970; Trifunac and Hudson, 1970; Trifunac *et al.*, 1971; Trifunac, 1970, 1971). The errors of this process have been examined in detail; the special problems of training operators to produce reproducible results have been solved; and it was possible to apply the experi-

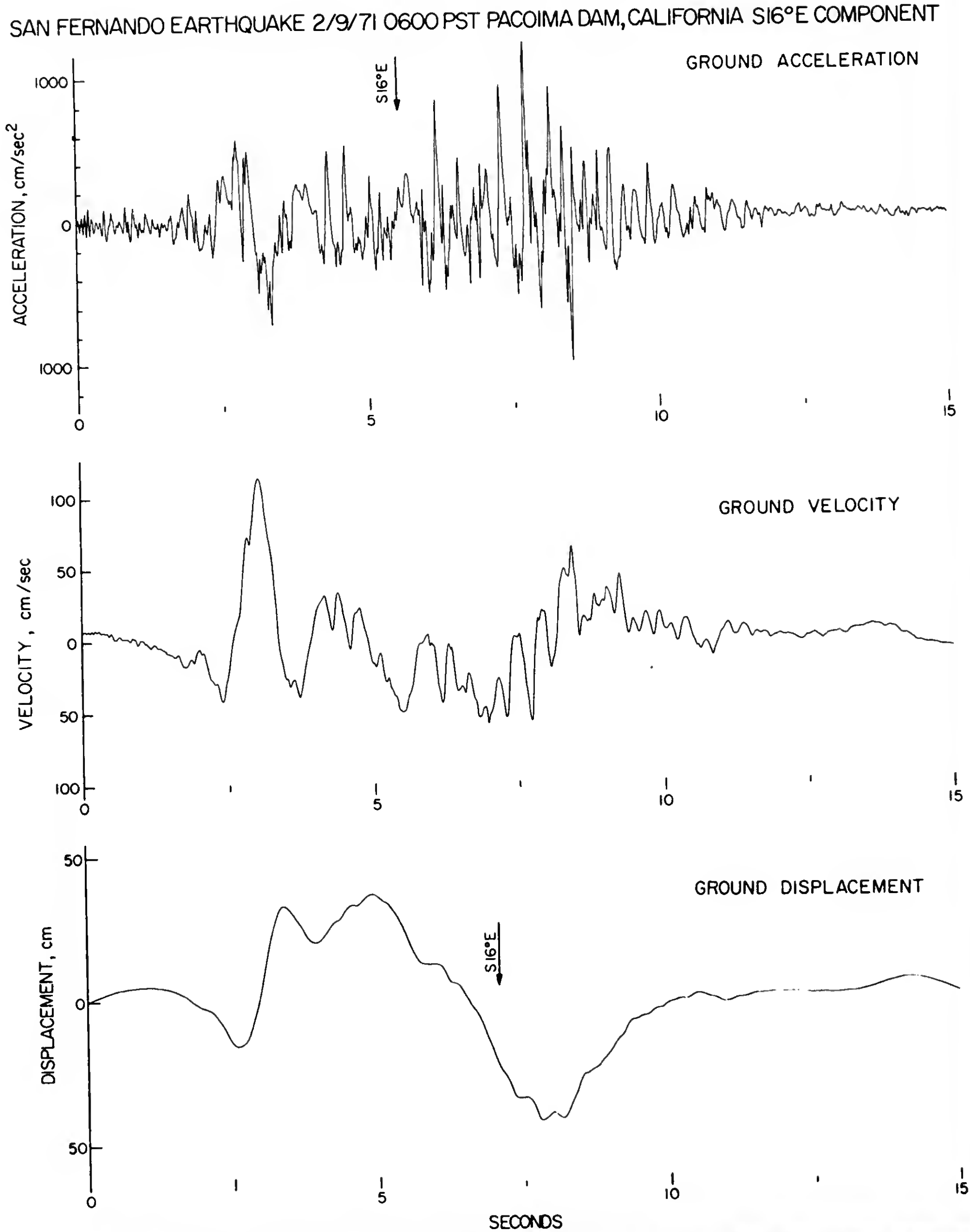


Figure 10. Computer plot of standard digitized data of S.16°E. component of the Pacoima Dam accelerogram, with integrated ground velocity and displacements.

ence directly to the treatment of the San Fernando records (Hudson, 1971).

For each record, reproduction of a computer plot plus a complete print-out of the digitized record is being published in the series of reports "Strong-Motion Earthquake Accelerograms — Digitized and Plotted Data, Volume I, Uncorrected Accelerograms," Earthquake Engineering Research Laboratory, California Institute of Technology. At the time of the San Fernando earthquake, Vol. I, Parts A and B, containing 40 records from past earthquakes, had been published. Because of the special importance of the San Fernando earthquake, the sequence of past earthquakes was interrupted, and Vol. I, Part C (dated July 1971), contains the first of the San Fernando series (Brady *et al.*, 1971).

During the past few years, several automatic digital imaging processes have been developed for special applications, such as the digitization of space photographs, and of bubble-chamber tracks for particle physics investigations. Several of these systems are directly applicable to accelerograph digitization. The main problems in the use of such equipment are (1) the availability of the special equipment, (2) the relatively complex computer programming involved, and (3) establishing accuracy of the process. Sample earthquake accelerograms have been digitized on a representative completely automatic system, and it appears that satisfactory results can be obtained at an attractive cost figure. For future earthquake accelerogram analysis, such automatic systems offer considerable promise and will no doubt be widely applied.

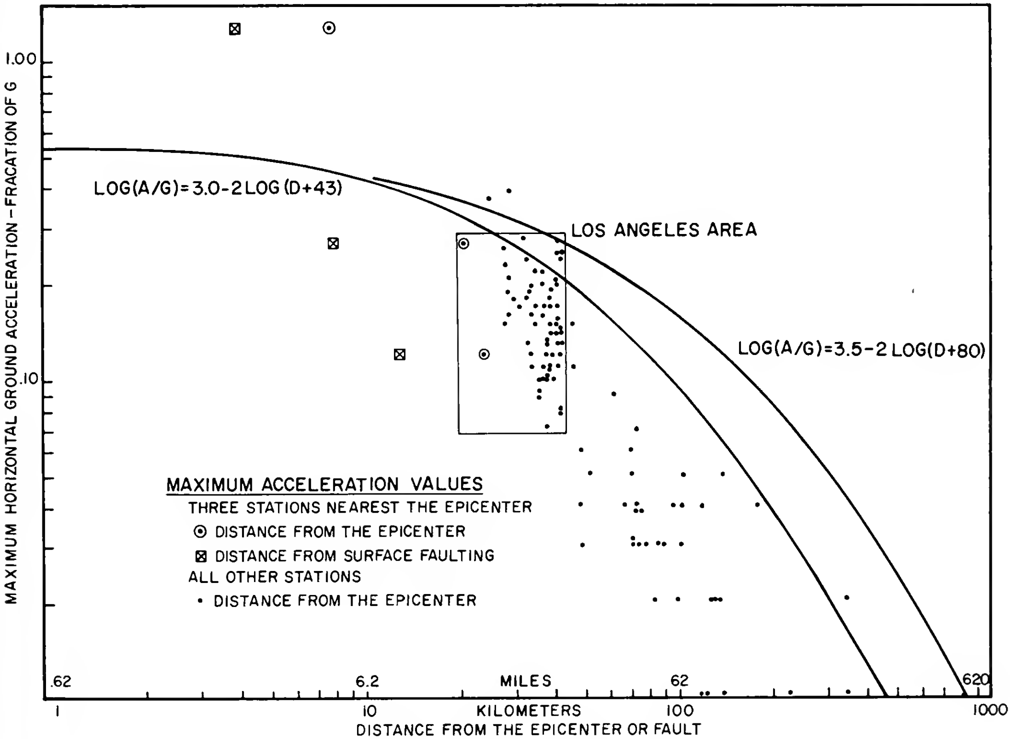


Figure 11. Maximum horizontal ground accelerations ($a \geqq 0.019$) recorded during the San Fernando earthquake.

In digitizing accelerograms from the San Fernando Earthquake, priority was given to those records needed by engineers studying particular buildings.

Once the digitized data are available, it is a relatively simple matter to carry out a number of important calculations. One of these is the computation of integrated ground velocity and displacement curves from the accelerograms. Various errors involved in these computational processes have been examined in detail in previous investigations, and standard methods had been evolved which could be applied directly to the San Fernando accelerograms (Trifunac and Hudson, 1970; Trifunac *et al.*, 1971; Trifunac, 1970; Trifunac, 1971; Hudson, *et al.*, vol. II, 1971). Similarly,

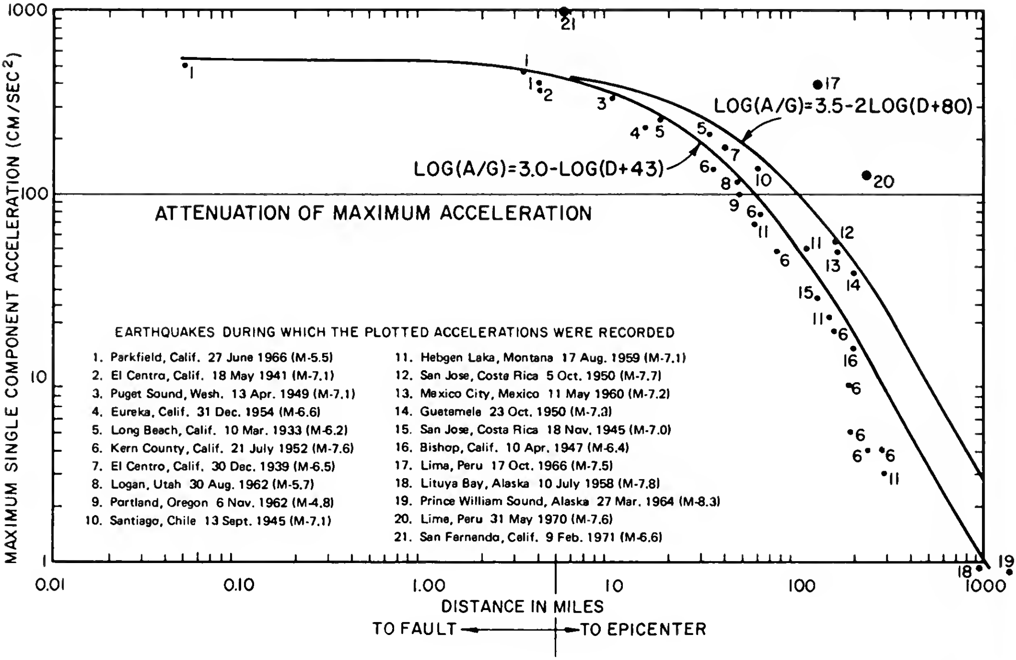


Figure 12. Maximum accelerations recorded at various distances during the 40-year history of the strong-motion recording program. Envelope equations were developed prior to earthquakes 17, 20, and 21.

the calculation of response spectrum curves and of Fourier spectra have been extensively investigated, and suitable computer programs had been worked out which were available for direct application (Hudson *et al.*, vols. III and IV, 1971). A number of these calculations have already been completed, but in view of the large number of records available, and of the time required for publishing the reports, it will be a matter of several years before the whole backlog of past strong-motion earthquake accelerograms can be completed.*

Figure 10 shows an example of a computer plot of a corrected strong-motion accelerogram, along with the calculated integrated ground velocity and displacement. Figure 13 is a plot of the response spectrum to correspond with the component of acceleration shown in figure 10 for Pacoima Dam. Figures 14 and 15 are additional examples of response spectrum calculations and will indicate one form in which all the records will be ultimately available.

APPLICATION OF ACCELEROGRAPH RESULTS

The information contained in the accelerograms can be used in several different ways to carry out fundamental investigations in earthquake engineering and strong-motion seismology. Some of these applications will now be outlined, along with specific examples.

EARTHQUAKE SOURCE MECHANISMS

The accelerogram obtained at Pacoima Dam, virtually at the center of the epicentral region and directly over the main thrust fault involved in the earthquake, offers an unparalleled opportunity for studies of earthquake source mechanisms. Not only was the main shock recorded, but, as was mentioned above, the initial sequence of some 30 aftershocks immediately following the main shock was also recorded. From this continuous record of the main shock and its immediate aftershocks, basic source parameters such as stress drops, seismic moments, magnitudes, and spectral properties have been determined for comparison with later aftershocks in the developing pattern of propagating fracture (Hudson *et al.*, vol. IV, 1971; Trifunac, 1971). This initial aftershock information fills an important part of the gap in the data before the regular seismological instrumentation began to acquire aftershock information. A complete analysis of the earthquake taking into account the whole sequence of events and comparisons with distant recordings will no doubt considerably advance current understanding of earthquake source mechanisms.

* In the meantime, such data will be available on request on an individual basis for the more important sites.

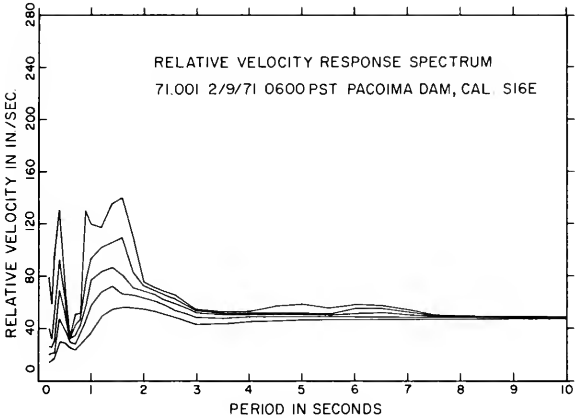


Figure 13. Relative velocity response spectrum calculated for the S.16°E. component of the Pacoima accelerogram.

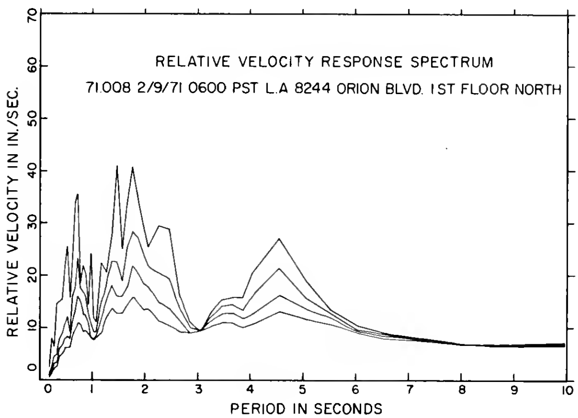
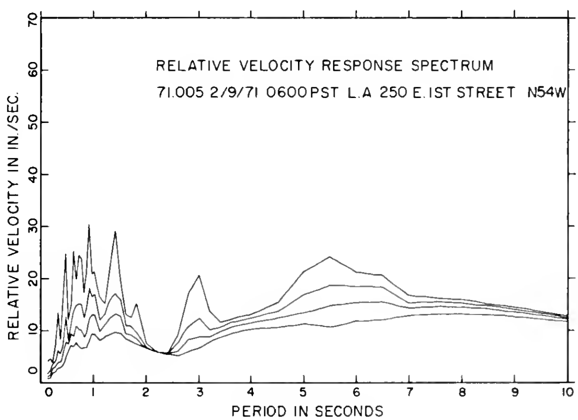


Figure 14. Preliminary relative velocity response spectrum for 8244 Orion St. Station, horizontal component, North, 20 km from epicenter.

Figure 15. Preliminary relative velocity response spectrum for the 250 E. First St. Station, horizontal N.54W. component, 41 km from epicenter.



LOCAL DISTRIBUTION OF EARTHQUAKE GROUND MOTION

A second important application of the accelerogram is to describe the variation of ground shaking over the area affected by the earthquake in accurate quantitative terms. Although there were not as many accelerograph stations in the immediate vicinity of the epicentral area as one would have liked, there were enough in various directions to clearly indicate the great complexity of the pattern of ground shaking. Stations to the north of the epicenter, such as Castaic and Lake Hughes, showed in some cases unusually high peak accelerations compared with stations at a similar distance to the south. The explanation for such variations must be sought for in local geological conditions and in variations in travel path geometrics and will no doubt result in a more realistic appraisal of the true complexity of the problem.

The distribution of ground shaking over the entire southern California region is indicated by the maps of figures 2, 3, and 4. At each accelerograph station, the peak ground acceleration in fractions of gravity is indicated. This quantitative description of the distribution of ground shaking is of course a key feature in an understanding of the effects of the earthquake on structures and makes it possible to carry out a much more detailed investigation of the implications of the event for the development of earthquake resistant design than has been feasible for any previous earthquake. Taken in connection with the seismoscope results, which fill in additional details of local distribution, the detail obtained in this earthquake is better by orders of magnitude than has been obtained in any past earthquake.

A preliminary evaluation of the general pattern of ground motion distribution tends to suggest that the true state of affairs as revealed by the measurements is rather more complicated than had been contemplated by certain simplified models. It seems highly unlikely that any single factor, such as thickness of soil layers, distance from faults, etc., will be adequate for even a rough description of the pattern.

The acceleration measurements should also make it possible to enhance the significance of isoseismal intensity maps based on postcard surveys. By correlating varying aspects of the acceleration measurements with the Modified Mercalli intensities, it may be possible to improve the usefulness of these subjective evaluations. Since such intensity data are the only information available for many important earthquakes of the past, as well as for many current earthquakes occurring in regions with little strong-motion instrumentation, they will be of great importance to improve the intensity values.

THE EARTHQUAKE AS A STRUCTURAL DYNAMIC TEST

A third important application of the accelerograms is to the calculation of the dynamic structural properties of buildings in which multiple accelerographs had been placed. In 1965 the City of Los Angeles added to its building code a requirement that three strong-motion accelerographs should be installed in each new structure over six stories in height. One of these instruments was to be installed in the basement to record the input earthquake ground motion, and the other two were to be placed at the top of the building and at an intermediate location to describe the earthquake response of the structure. In 1970 the Uniform Building Code adopted this accelerograph regulation in an appendix which was adapted by a number of cities. At the time of the earthquake, over 50 buildings were instrumented under these regulations, and these code stations thus constituted by far the major source of accelerographs for the southern California network.

Figure 8 shows a typical set of three accelerograms from a building, in this case the instrumented building nearest the epicenter (20 km). It will be noted that the peak ground acceleration was 0.27 g, while the 8th floor roof showed peak accelerations of 0.39 g. Although these acceleration values are considerably larger than would be contemplated by the seismic design force specifications of the building code, no significant structural damage was suffered by the building. There was, however, a considerable amount of nonstructural damage to the building and its contents, which cost approximately $100,000 to repair. The situation at this building is a good example of the way in which accelerograph readings make it possible to study the true structural characteristics in considerable detail. Without the measurements, it would have been virtually impossible to have inferred from the appearance of the building and its contents what the ground motions had actually been, and estimates of input forces might well have been off by a factor of 2 or 3.

In table 3a and b are shown some typical multistory buildings for which complete acceleration data were obtained during the earthquake. It will be noted that peak accelerations of the order of 0.40 g were not uncommon at upper floor locations. When it is remembered that the highest accelerations to which it has been possible to excite full-scale multi-story buildings by means of vibration-generator test equipment is of the order of 0.03 g to 0.04 g, it will be seen that the earthquake has involved accelerations of about 10 times the magnitude of past tests. The earthquake may thus be thought of as a structural dynamic test on a vast scale. At one stroke, some 50 structures have been dynamically tested under measured conditions at force levels far beyond the capabilities of any other test procedure.

STRUCTURAL RESPONSE

As an example of the way in which the accelerograph records can be used to interpret such dynamic tests of structures, the results of an analysis of the Kajima Building will be outlined. A notable investigation of this structure has been conducted by Dr. K. Muto (1971) of the Kajima Corporation, based on the accelerograms. Figure 16 shows schematically the way in which the actual structure is represented by a simplified mathematical model. The initial object of the investigation is to define the model numerically and to verify its general appropriateness and accuracy by showing that it can in fact represent the measured response of the actual building to this particular earth-

Table 3. Typical peak accelerations (g's) in multi-story buildings: steel-frame—San Fernando Earthquake of February 9, 1971; H1, H2 = Orthogonal Horizontal Components: V = Vertical

No.	Building	Date	No. Stories	Ground, Basement or 1st Floor			Intermediate Level			Roof or Top Floor		
				H1	H2	V	H1	H2	V	H1	H2	V
1	5260 Century*	1968	7	0.06	0.05	0.02	0.05	0.07	0.04	0.07	0.05	0.09
2	3407 Sixth	1966	8	0.17	0.20	0.06	0.22	0.22	0.10	0.28	0.22	0.27
3	1150 Hill	1970	10	0.12	0.09	0.05	0.10	0.12	0.09	0.12	0.12	0.15
4	900 Fremont	1971	12	0.14	0.14	0.07	0.14	0.15	0.12	0.18	0.15	0.17
5	L.A. Water and Power	1969	15	0.15	0.20	0.08	0.19	0.14	0.09	0.17	0.13	0.16
6	250 First	1967	15	0.10	0.14	0.06	0.21	0.17	0.09	0.17	0.18	0.20
7	1800 Century Park East	1970	16	0.08	0.11	0.08	0.23	0.25	0.16	0.28	0.28	0.33
8	800 First	1969	33	0.09	0.14	0.06	0.13	0.19	0.17	0.17	0.27	0.25

* Shear Wall.

Table 3a. Typical peak accelerations (g's) in multi-story buildings: reinforced concrete—San Fernando earthquake of February 9, 1971; H1, H2 = Orthogonal Horizontal Components: V = Vertical

No.	Building	Date	No. Stories	Ground, Basement or 1st Floor			Intermediate Level			Roof or Top Floor		
				H1	H2	V	H1	H2	V	H1	H2	V
1	15107 Vanowen	1970	7	0.11	0.11	0.11	0.24	0.23	0.20	0.36	0.40	0.17
2	8244 Orion	1967	7	0.25	0.15	0.19	0.21	0.25	0.24	0.40	0.34	0.26
3	1640 Marengo	1966	7	0.14	0.15	0.09	0.15	0.27	0.13	0.25	0.44	0.15
4	4680 Wilshire	1967	7	0.14	0.10	0.09	0.23	0.19	0.12	0.24	0.30	0.15
5	646 Olive*	1967	7	0.22	0.26	0.09	0.25	0.25	0.13	0.39	0.48	0.26
6	4687 Sunset	1966	8	0.20	0.18	0.15	0.31	0.24	0.15	0.45	0.47	0.22
7	2011 Zonal	1966	9	0.08	0.08	0.07	0.20	0.17	0.10	0.23	0.21	0.11
8	433 Oakhurst	1970	10	0.09	0.06	0.03	0.14	0.14	0.04	0.27	0.27	0.10
9	120 Robertson	1966	10	0.10	0.10	0.04	0.18	0.19	0.10	0.33	0.28	0.12
10	420 Roxbury	1969	10	0.21	0.17	0.05	0.21	0.24	0.11	0.30	0.22	0.14
11	7080 Hollywood	1966	11	0.11	0.11	0.08	0.21	0.13	0.16	0.21	0.13	0.22
12	3710 Wilshire*	1966	11	0.17	0.16	0.09	0.29	0.17	0.11	0.22	0.38	0.17
13	3470 Wilshire	1966	12	0.15	0.12	0.06	0.21	0.22	0.11	0.22	0.25	0.15
14	8639 Lincoln	1969	12	0.04	0.03	0.03	0.09	0.08	0.09	0.13	0.13	0.06
15	15250 Ventura	1971	12	0.17	0.24	0.11	0.25	0.28	0.16	0.18	0.30	0.18
16	2500 Wilshire	1969	13	0.11	0.13	0.06	0.14	0.16	0.07	0.20	0.20	0.15
17	6200 Wilshire	1970	16	0.12	0.13	0.03	0.29	0.17	0.05	0.28	0.27	0.08
18	4000 Chapman	1970	19	0.02	0.02	0.02	0.05	0.04	0.03	0.06	0.06	0.04

* Shear Wall.

quake.

The lowest curve of figure 17 is the acceleration time record obtained in the basement during the earthquake. The upper solid curves are the measured accelerations recorded at upper floor locations during the earthquake. The dotted curves are the calculated responses using the mathematical model of figure 16 with the measured basement acceleration as the input motion. The numerical parameters of the mathematical model such as stiffnesses and damping values were in effect adjusted by varying them over small ranges so that the calculated and measured accelerations agreed as closely as possible over the duration of the record. The excellent agreement obtained indicates that the relatively simple mathematical model of figure 16 does in fact result in a reasonably accurate representation of the actual structure.

Having once established the validity of the mathematical model, the distribution of such factors as the shear forces can be calculated for all floors. Figure 18 summarizes this shear force distribution for the Kajima Building. The curve on the left gives the standard design seismic shear forces as presented by the lateral force provisions of the Structural Engineers Association of California seismic code. The middle curve represents the measured shears during the San Fernando earthquake, determined as described above. The right-hand curve represents the ultimate strength limiting conditions at the various floors. It will be noted that, although this particular earthquake loaded the structure to about twice the code design values, the ultimate resistances were not approached. This illustrates in a graphic way the possible large gaps between the prescribed code forces and the ultimate resistances. It is of course always advisable to provide a suitable margin of safety between design forces and ultimate resistances, but it is also important in the interests of economy that this margin be reasonably uniform throughout the structure and that its true value be known.

Having learned from the above analysis the extent to which the dynamical calculations agree with measurement, the response of the building to other input ground motions can now be carried out with some assurance. In this way, the important question as to how the building would have performed had it been located in the epicentral region can be answered with a reasonable accuracy. By carrying out an analysis of the above type for all of the instrumented buildings in the Los Angeles region, the very important question of how modern high-rise buildings will behave under the highest possible seismic forces can be answered without waiting for the destructive earthquake itself. Without the accelerograph measurements, it would of course be virtually impossible to answer this critical question with any degree of assurance.

CODE DESIGN FORCES

The acceleration values measured during the San Fernando earthquake were considerably larger than had been generally anticipated for an event of that size. It has of course always been recognized that the lateral force coefficients specified in earthquake-resistant design codes are not to be directly equated to earthquake ground accelerations. Such coefficients must always be considered as an integral part of a whole design technique, involving standardized calculation procedures, prescribed allowable stresses, and a thorough knowledge of standard constructional details. On the basis of the San Fernando measurements, it is clear that the prescribed lateral force coefficients seriously underestimate the actual seismic forces. The performance of most structures also makes it clear that the true ultimate resistance of most structures have also been underestimated. These two underestimations cannot always be expected to exactly compensate. The earthquake demonstrated forcefully that, although this standard design philosophy may result in many satisfactory structures of a conventional type, there may be disastrous exceptions. The new buildings which collapsed with loss of life at the Olive View Hospital satisfied the specific requirements of the building code, but they did not meet the all-important

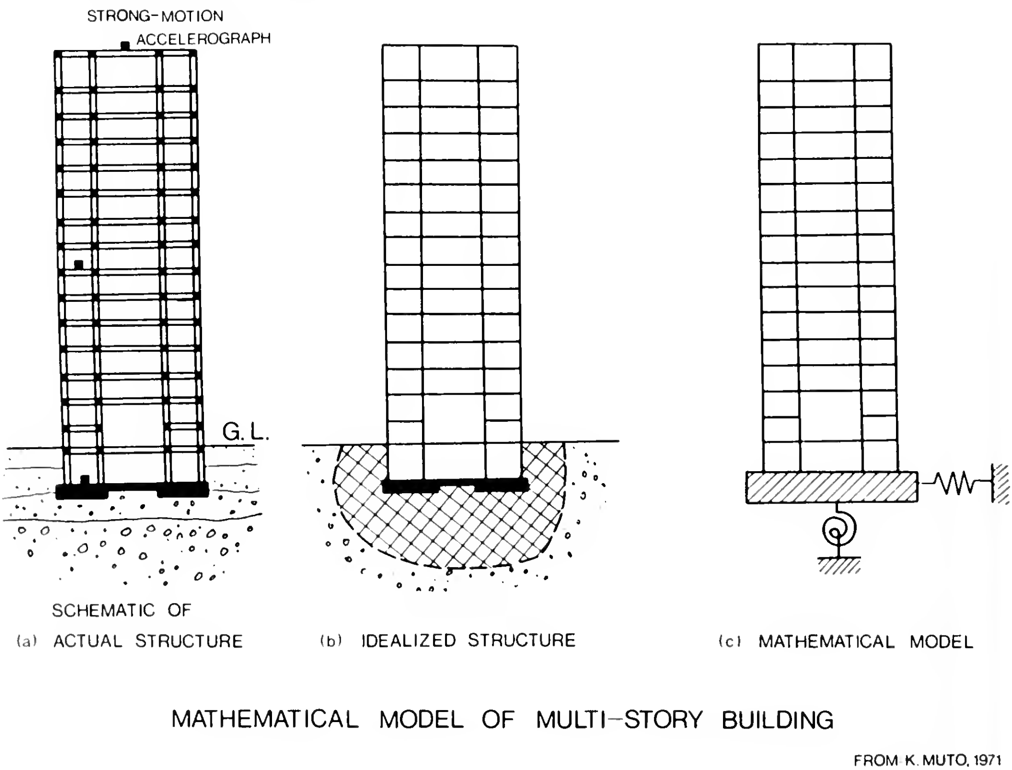


Figure 16. Schematic diagram and mathematical model for the Kajima building.

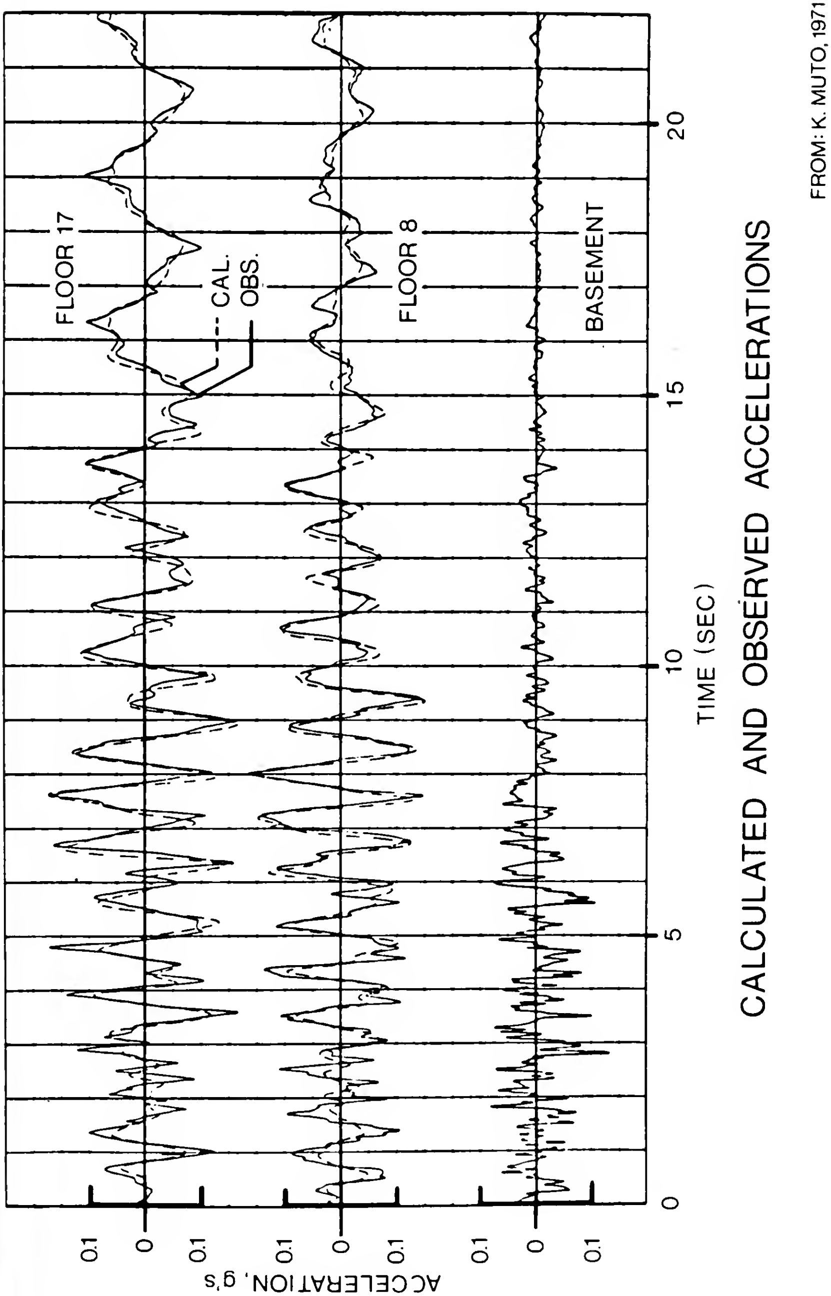


Figure 17. Measured and calculated accelerations in the Kajima building.

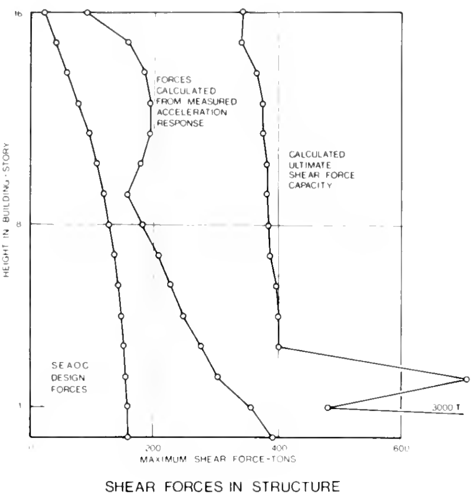


Figure 18. Calculated shear forces in the Kajima building.

criterion of safety against hazardous collapse. Structural engineers now face the very important problem of reformulating the basic earthquake-resistant design codes to keep step with the rapidly improving knowledge of the basic nature of earthquake motions and forces and with ever-improving methods of structural analysis.

NATURAL PERIOD MEASUREMENTS

The accelerograph measurements in buildings throw a considerable light on another aspect of structural dynamic analysis, involving the determination of the natural periods of structures.

A relatively simple measurement which will reveal significant information about the dynamic properties of a structure is an experimental determination of the natural periods of vibration (Housner, 1962; Hudson, 1971). Since the natural period involves both the mass and the flexibility of a structure, an experimental verification of a calculated period will provide a useful check on the validity of both the mathematical models and the numerical values employed.

Another application of natural period information involves the idea that large building vibrations caused by a damaging earthquake might result in permanent changes of the period. Such changes have in fact been observed during past earthquakes (Esteva y Nieto, 1967; Cloud and Maley, 1970). It might thus be possible to infer from a measured change in natural period during an earthquake that significant structural damage had occurred which might not be evident from a superficial examination of the building. In that event, a relatively expensive structural examination might be justified. Such studies can be made only if there exists a large body of pre-earthquake period measurements to form a basis of comparison with post-earthquake measurements. This has been the motivation behind an extensive program of determination of natural periods of structures carried out by the Seismological Field Survey of the National Oceanic and Atmospheric Administration.

The natural periods of buildings are usually determined by recording small vibrations caused by wind excitations. The motions are of course much smaller by several orders of magnitude than those associated with damaging forces, and one of the main questions involves the extent to which properties determined at these very low levels can be extrapolated to larger excitation. The information obtained during the San Fernando earthquake from the building accelerographs goes a long way towards clarifying this situation.

In table 4 are shown data from several buildings for which low-level period measurements are available both before and after the earthquake and can be compared directly with values obtained during the much larger motions of the earthquake. The records of figure 19 are typical. The low-level wind-excited and man-excited (Kuroiwa, 1967) periods were determined unambiguously from records of the type shown in figure 19 (a and c). The accelerogram reproduced in figure 19 (b) shows that, after the initial transient part of the earthquake which excited simultaneously a number of modes of vibration, the building motion settled down into a clear single-frequency sinusoidal oscillation at its fundamental period, which is clearly evident on the record and can be directly measured with considerable accuracy.

A very important fact which emerges from table 4 and figure 19 is that the period of the building during the relatively large motions of the earthquake is considerably longer than the low-level periods determined from the wind excitation. This pronounced nonlinear behavior must always be kept in mind when comparing periods of mathematical models with periods experimentally determined. It is hoped that a study of the very complete data obtained during the San Fernando earthquake will permit an accurate assessment of these nonlinear effects.

Although table 4 indicates that there was a considerable permanent shift in natural period caused by the earthquake in many buildings, apparently none of the buildings suffered significant structural damage. The potential usefulness of period shifts as an indication of hidden damage thus becomes questionable. If even larger period changes can occur without serious structural damage, it may be difficult if not impossible to decide the amount of period shift for a particular structure which should be taken as an indication of structural damage rather than nonstructural damage. It is hoped that detailed studies now being made of a number of the instrumented buildings will provide a definitive answer to such questions.

SEISMOSCOPE RESULTS

In addition to the time-recording strong-motion

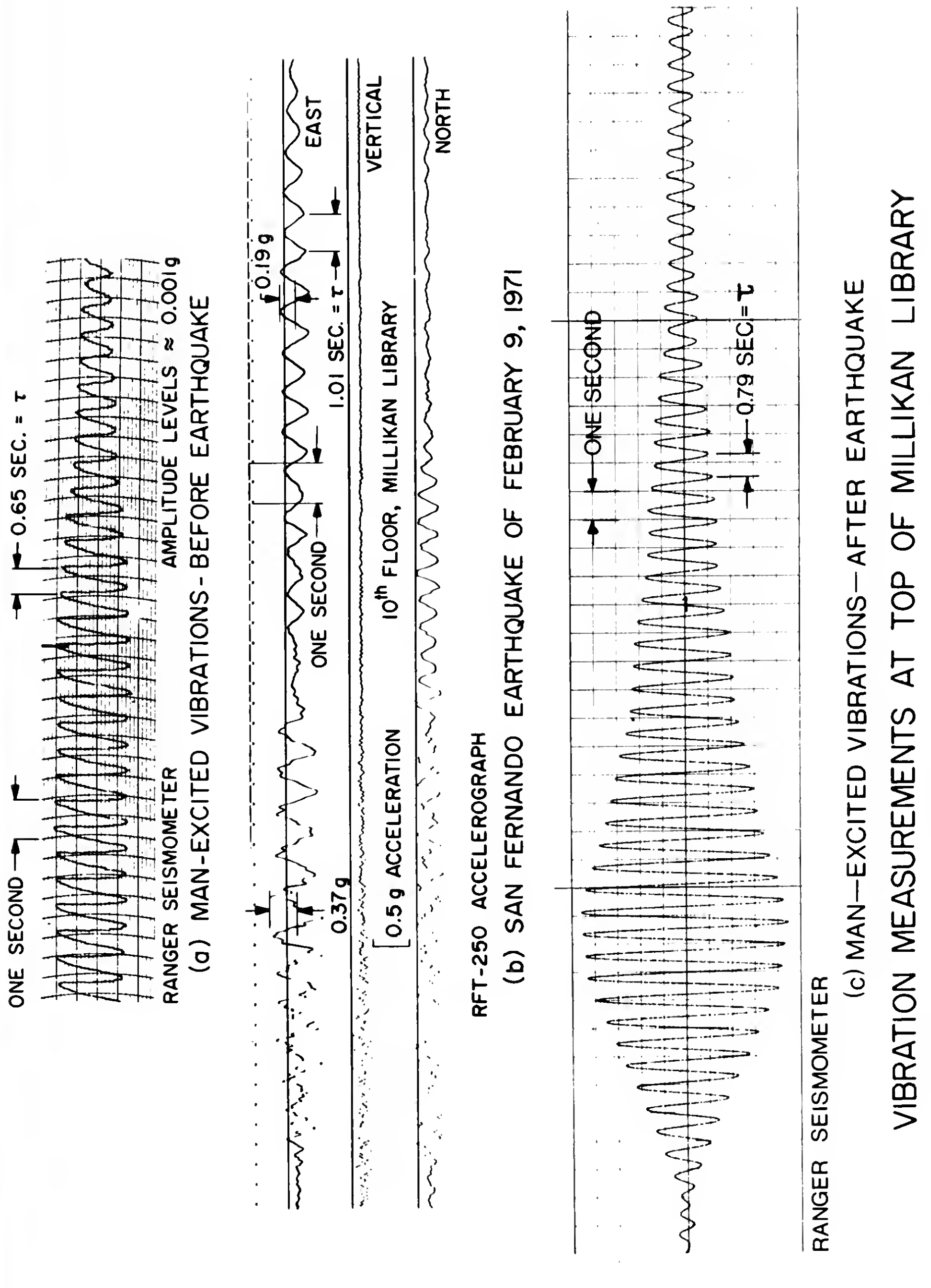


Figure 19. Vibration measurements at top of Millikan Library, showing effects of the San Fernando earthquake.

Table 4. Selected building periods measured before, during, and after the San Fernando earthquake.

Building	*No. of Stories*	*Type Frame*	*Epicentral Distance (km)*	*Direction*	*Max. Ground Accel. (%)*	*Fundamental Period (sec)*		
						Pre-Eq.	*During Eq.*	*Post Eq.*
8244 Orion	7	R-C	20	N	27	0.48	1.6	0.65
				W	14	0.52	1.3	0.70
J. P. L.	9	ST	29	S 08 W	17	0.99	1.4	1.16
				S 82 E	21	0.93	1.3	1.01
7080 Hollywood	11	R-C	34	N	10	0.90	1.4	1.02
				E	11	1.03	1.5	1.14
3710 Wilshire	11	R-C	39	S	16	0.98	1.4	1.07
				W	17	0.76	1.1	0.87
611 Sixth St.	43	ST	41	N 52 W	10	4.5	5.6	5.3
				N 38 E	11	4.7	6.0	5.3
420 Grand	16	ST	41	S 37 W	12	0.69	0.97	0.85
				S 53 E	17	0.68	1.04	0.88
1640 Marengo	7	R-C	42	N 38 W	14	0.53	1.0	0.65
				S 52 W	14	0.49	1.2	0.64

accelerographs that constitute the main source of information from the strong-motion network, there are in the southern California region over 120 seismoscopes which provide valuable supplementary data.

The seismoscope is a simplified device which directly records for all horizontal directions of one point on the response spectrum curve. It consists of a free conical pendulum which can move in any horizontal direction. The wire flexure pivot support point of the pendulum moves with the ground, and the resulting angular deflections relative to the instrument frame are recorded by a scriber on a smoked spherical watch glass. Eddy current damping is provided by an aluminum disk in the form of a segment of a spherical shell, which moves between the poles of a permanent magnet system. Since the motion in the horizontal plane is traced out as a permanent record, the sequence of events can be followed even though no time-recording is employed and the directions of maximum motions are indicated.

The natural period of the seismoscope pendulum is a nominal 0.75 seconds, and the damping is adjusted to approximately 10 percent of critical damping. These values give a response spectrum point near the middle of the range of structural interest and hence provide in a physically meaningful way a quantitative measure of the damaging effects of the earthquake. Since 15 to 20 seismoscopes can be acquired for the cost of one time-recording accelerograph, the seismoscope can be effectively used to fill in gaps in the network coverage and thus to supplement the more complete information obtained from the accelerographs.

The map of figure 20 shows the seismoscope sites producing records during the San Fernando earthquake. Centered on each station is a line segment whose length is proportional to the maximum excursion on the seismoscope plate and whose direction indicates the direction of the maximum response. Some 120 records were obtained, and it is evident from figure 20 that the readings reveal in a striking way the great complexity of the pattern of local distribution of heavy ground shaking. Tabular values of the spectrum responses and of associated information such as distance from the epicenter were compiled in Hudson's report (1971).

In figure 21 are shown several examples of seismoscope records photographed directly from the original glass record plates. In all figures, North is upward, and the diagonal line is the N.67W. direction which approximates the strike of the fault.

The two sites of figures 21 (a) and (b) are located less than half a kilometer apart on the same geological and soil conditions consisting of 250–300 m of old alluvium over crystalline rock. The somewhat larger values of figure 21 (a) perhaps reflect a difference in the interaction between the 9-story reinforced concrete Millikan Library building and the foundation soils, compared with the 2½-story concrete Athenaeum building. Accelerograph recordings were made at the same sites, and further studies will be necessary to fully explain the situation.

A comparison of figures 21 (a) and (b) with figure 21 (c) is also instructive. The station at the Seismological Laboratory figure 21 (c) is located on a crystalline rock of a granitic character, weathered

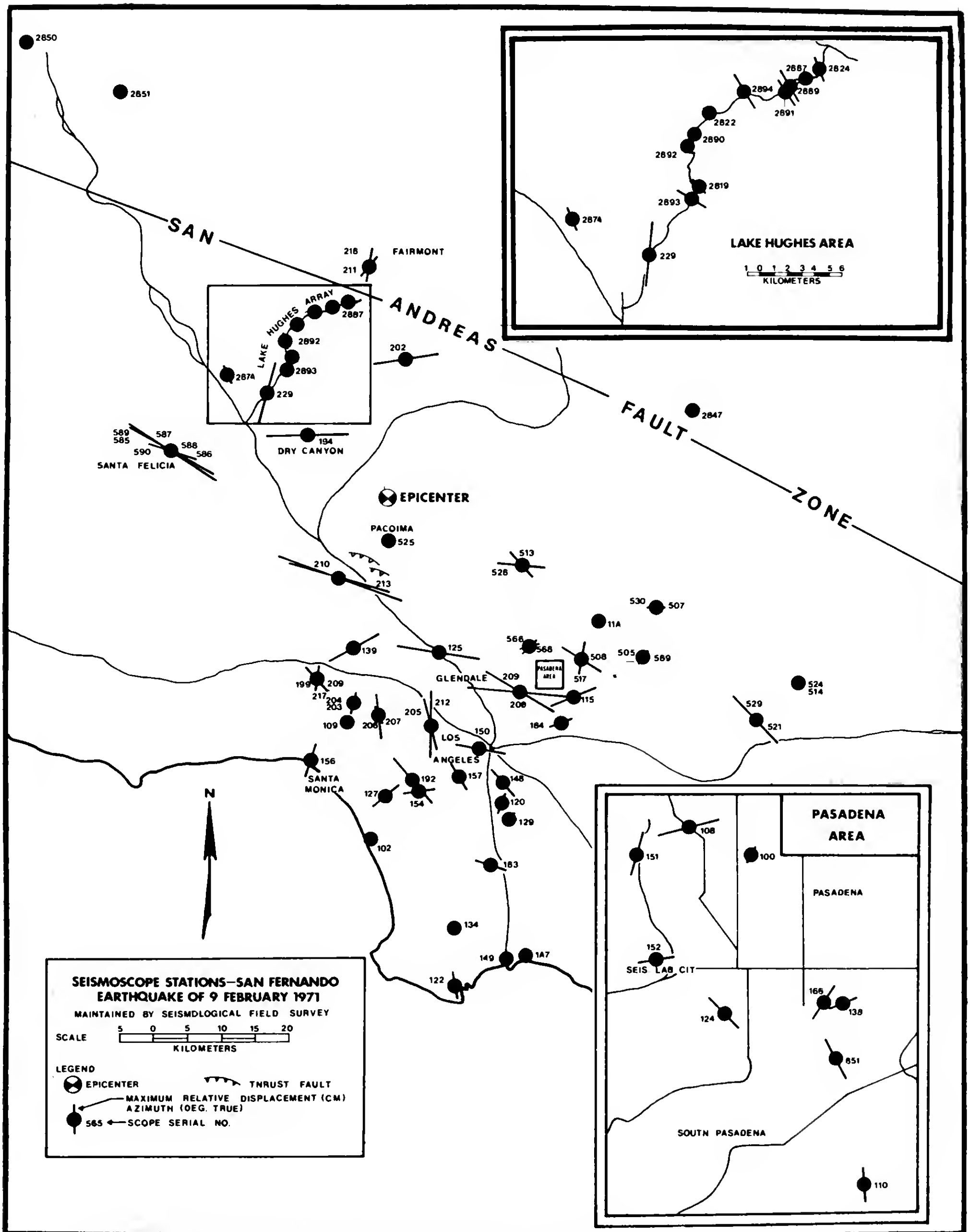
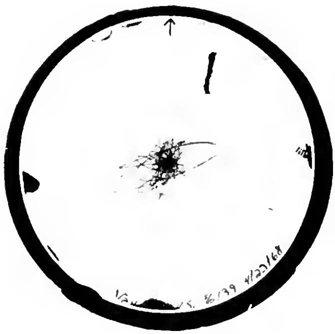


Figure 20. Seismoscope stations recording the San Fernando earthquake showing maximum relative displacement spectrum values.

MILLIKAN LIBRARY CALTECH CAMPUS
384 KM

ATHENAEUM–CALTECH CAMPUS
386 KM

SEISMOLOGICAL LAB–CALTECH
35 0 KM



VAN NUYS HIGH SCHOOL
241 KM

EAGLE ROCK RESERVOIR W ABUT
36 2 KM

EAGLE ROCK RESERVOIR CREST
36 2 KM

Figure 21. Seismoscope record examples of the San Fernando earthquake.

near the surface. Comparisons made between ground motions measured at the Seismological Laboratory and at the Caltech campus for small earthquakes have shown on the average significantly higher motions at the campus (Gutenberg, 1957). For the San Fernando earthquake, however, in the same period ranges, the motion on the rock at the Seismological Laboratory was somewhat larger than on the campus alluvium. This conclusion is also confirmed by accelerograph recordings at the same two sites. In addition, it can be noted from figure 21 (c) that the motion at the Seismological Laboratory was almost uni-directional, to a more striking extent than at any other station in the whole network. This indicates how the seismoscope can reveal certain significant details of strong ground motion.

The two lower figures of figure 21 show unusually large responses on the abutment and crest of the dam at Eagle Rock Reservoir. Referring to the map of figure 20 it will be seen that these appear to be anomalously high values for the distance from the epicenter, although they seem to be part of a band of unusually high values following along the base of the mountains. The record of figure 21 (d) from the Van Nuys High School is another example of large values, in this case showing excellent detail.

The seismoscope records from the abutment and crest of the lower San Fernando Dam are of unusual interest as they are the only measurements of the strong ground shaking at this important site, other than one peak-reading accelerograph on the failed crest. In view of the great importance of a complete study of the failure of the dam, a special effort has been made to deduce from the seismoscope record on the abutment approximate values of the ground acceleration (Scott, in press). A recovery of the ground acceleration-time history from the seismoscope plate can in theory be accomplished, but in practice it is only under certain specially favorable conditions that a useful accuracy can be attained. In the case of the Lower San Fernando Dam, it is believed that the accuracy of the response spectrum curves calculated from the acceleration-time record derived from the seismoscope record is of the order of 10–20 percent.

SUMMARY

The main shock of the San Fernando earthquake (Richter magnitude 6.5 BRK, 6.4 PAS; Modified Mercalli Scale maximum intensity XI; felt area 80,000 square miles) was recorded by 241 accelerographs and 120 seismoscopes. These more than double the number of strong-motion instrument records that were available prior to the earthquake.

Among the more significant results from preliminary analysis of the records are the following:

1. The highest earthquake accelerations ever measured, 1.25 g horizontally and 0.72 g vertically, were recorded on the abutment of Pacoima Dam, 8 km from the reported epicenter. The previous maximums were 0.5 g, recorded a few hundred feet from surface faulting on alluvium during the June 27, 1966, Parkfield, California, earthquake, and about 0.6 g recorded at Koyna Dam, India, December 11, 1967.

2. Except for the high frequency peak accelerations at Pacoima Dam, attenuation of maximum ground acceleration with distance from epicenter is reasonably consistent with the empirical equations developed from earthquakes recorded in the past.

3. The large values of the Pacoima Dam site maximum accelerations coupled with additional large high-frequency acceleration peaks from Peruvian earthquakes and from Koyna, India, indicate a need to investigate in more detail accelerations in the period range below 0.1 sec.

4. During the earthquake, the fundamental periods of most instrumented buildings were considerably longer than those measured under light wind excitation before and after the earthquake.

5. Fundamental periods of many buildings measured after the earthquake under light wind excitation were found to be somewhat longer than when measured prior to the earthquake, indicating that the earthquake had caused some alteration in the dynamic properties of the structures. In no case was any significant structural damage associated with these period changes.

6. Peak acceleration exceeded 0.3 g on the top floors of 20 high rise buildings. No significant structural damage was observed.

The unprecedented amount of valuable data on strong earthquake-generated motion obtained during the San Fernando earthquake marks a major step forward in engineering seismology and indicates the additional information that may be anticipated from the rapidly increasing network of strong-motion instruments in the United States and other countries.

ACKNOWLEDGMENTS

Data prepared and previously published by M. D. Trifunac and A. G. Brady of the California Institute of Technology and R. P. Maley, B. J. Morrill, V. Perez, and Nina Scott of the Seismological Field Survey were of especial help in writing the present paper.

CHAPTER 23

A Preliminary Evaluation of the Effects of Topography on Ground Motion[1]

by Lawrence L. Davis [2] and Lewis R. West [2]

The ground motion at any particular site is a function of numerous parameters and variables acting at the source, along the transmission path, and at the local receiver site. In assessing the safety of any given site, accurate ground-motion predictions are required. The accuracy of the ground-motion predictions depends upon the degree to which the numerous interacting phenomena are understood and accounted for in the prediction.

The effects under consideration in this paper are those at and in the immediate vicinity of the recording site. Much work has been done toward understanding the effect of the rock and soil profile at the recording site (Murphy *et al.*, 1971; Schultz, 1967; Murphy and Davis, 1969), but a principal problem remaining in the area of recording site effects is the effect of topography on ground motion. Neither the extent to which ground motion might be affected by topography nor what the parameters of a topographic feature are that influence ground motion is known. The effects probably are not important when the seismic wave lengths are much longer than the dimensions of the topographic feature; however, since in many engineering applications short wave lengths (high-frequency motion) may be expected on steep slopes, the effects need to be better understood.

There is empirical evidence that topography does affect ground motion and, in particular, that motion can be amplified on the crest of a topographic feature. In 1968, Clarksmobile, a nuclear detonation at the Nevada Test Site, provided a hint that topography might be important. At numerous recording instruments deployed in and around Tonopah, Nevada, amplitudes recorded on mountain tops were larger than the amplitudes recorded in the valley.

More recently, Boore (1972) reported that churned ground and overturned boulders were observed following several earthquakes. These observations were noted only on ridge crests or other topographically high features. In the same paper, Boore examined calculated SH waves incident on three different topographic models and, using spectral ratios of the amplitudes at various points on the topographic feature, he found that amplitudes on the crest were amplified and that amplitudes along the flanks could either be amplified (to a lesser degree than on the crest) or damped depending on the geometry of the model and the position on the flank. As one might expect, his results showed that the amplification (or damping) is dependent upon the relationship between the dimensions of the topographic feature and the wave length of the incident wave; that is, the effects are frequency-dependent.

In another recent investigation (Aboudi, 1971), the effects of a small surface obstacle with slightly different properties than the elastic half-space were examined. The results showed that Rayleigh and reflected waves were influenced by the presence of a surface feature.

DESCRIPTION OF INSTRUMENTATION PROGRAMS

Two field programs obtained data on the effects of topography on ground motion. Seismic instruments were placed at the crest and at the base of Kagel Mountain and Josephine Peak during May 1971, while aftershocks from the February 9 San Fernando earth-

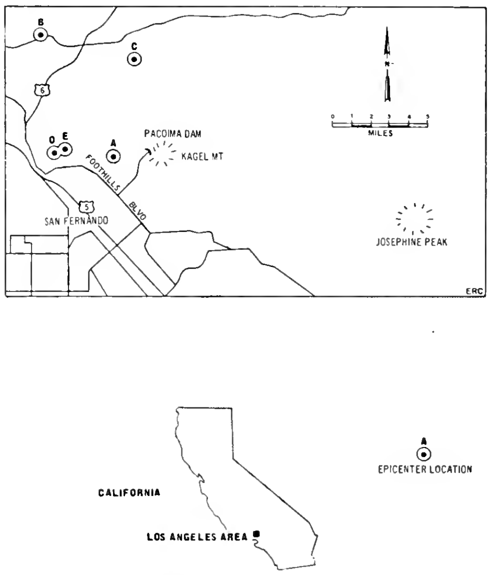


Figure 1. Location of Kagel Mountain and Josephine Peak in relation to aftershocks studied.

[1] Manuscript submitted for publication August 11, 1972.

[2] Staff scientist, Environmental Research Corporation, Las Vegas, Nevada.

quake were still occurring. Figure 1 shows the locations of the two mountains and the epicenters of aftershocks recorded. The mountains were selected because of their easy access via roads, uniform geology, and relatively simple geometry. Mountains with uniform geology were selected so that any difference between motions at the top and at the bottom of the mountains could be attributed to topography rather than geology.

Three component L-7 velocity-meter systems were installed and operated by the Special Projects Party of the Earth Sciences Laboratory, National Oceanic and Atmospheric Administration. King (1969) gave a detailed description of the L-7 velocity-meter system. One vertical and two horizontal (oriented north/south and east/west) seismometers were installed at each station—Station 82 on the crest of Kagel Mountain and Station 83 at the base of Kagel Mountain near Pacoima Dam. Station 80 was located on top of Josephine Peak, Station 81 was at the base of the peak in Tujunga Canyon. Figure 2 shows the configuration of Kagel Mountain and the location of the two seismic stations. Josephine Peak with its instrument location is illustrated in figure 3.

SEISMIC DATA

The velocity seismograms were processed to obtain acceleration and displacement time histories and pseudo relative-velocity (PSRV) spectra with 5 percent damping. PSRV spectra are useful for characterizing the spectral composition of a seismogram. The PSRV spectrum represents the peak response of an ensemble of single-degree-of-freedom oscillators to the input ground motion and, for low values of damping,

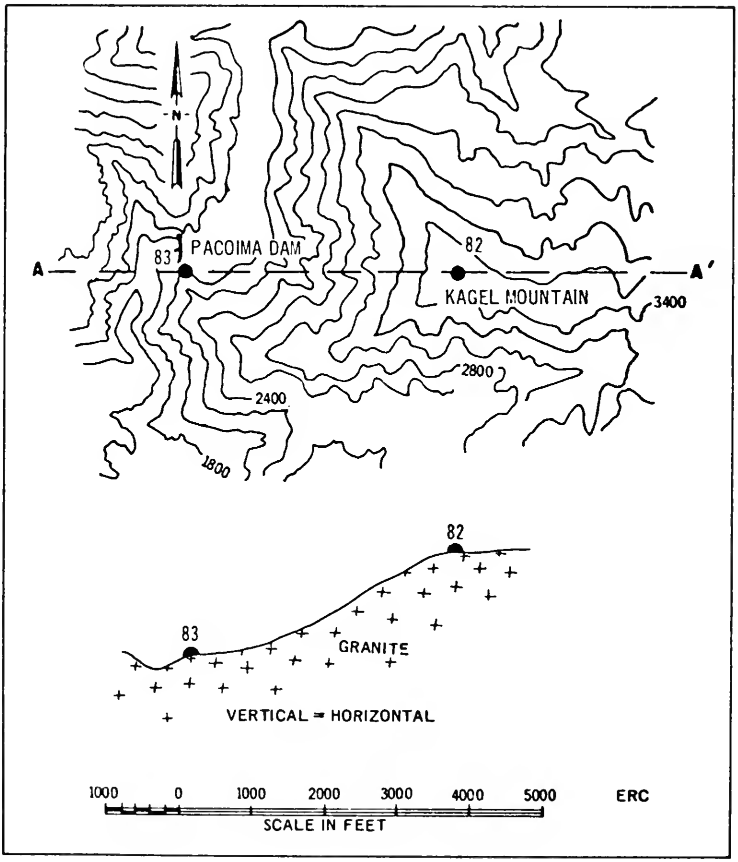


Figure 2. Topography, geology, and station locations, Kagel Mountain.

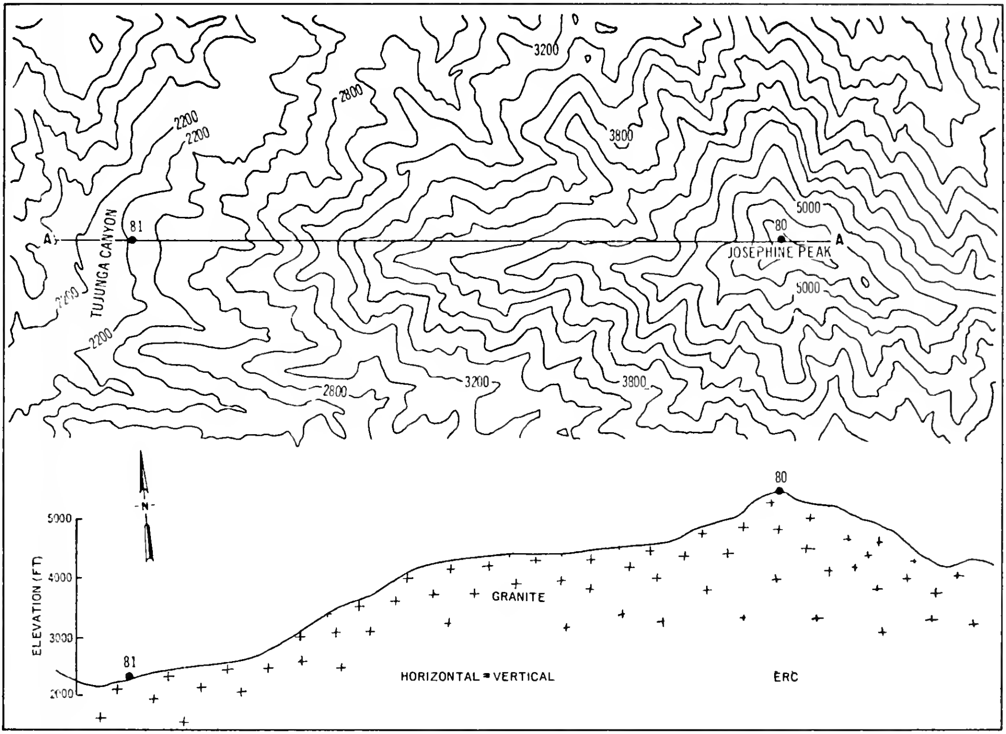


Figure 3. Topography, geology, and station locations, Josephine Peak.

is a close approximation to the Fourier amplitude spectrum (Lane, 1972).

Good-quality data were recorded at the crest of Kagel Mountain (Station 82) and at the base (Station 83, near Pacoima Dam); Station 82 recorded on only two components (vertical and north/south) while Station 83 recorded all three components of motion. Four aftershock signals recorded at the Kagel Mountain stations were selected for processing and analysis. At Josephine Peak, only two good-quality aftershock signals were recorded at both stations; all three components of motion were recorded.

DISCUSSION

The effects of topography can be determined by comparing the ground motion on a topographic feature with the motion recorded at the base of the feature. Any difference should be caused by topography as long as other effects, unrelated to topography, can be eliminated or minimized. These other effects would be caused by variations in the source, transmission path, or local receiver site regimes. Source effects were eliminated by taking crest-to-base ratios of the data separately for each aftershock. Transmission path effects were minimized by keeping the distance between the crest and base stations small relative to the distance between the aftershock epicenter and the suite of stations. The effects of local station geology were minimized by selecting mountains with uniform geology such that the crest and base stations could be placed on the same geologic material. PSRV spectral ratios (ratios of the motion at the top to motion at the bottom) are shown on figures 4 and 5 for Kagel Mountain and Josephine Peak. Crest-to-base ratios of the peak amplitudes are listed in table 1. The peak amplitude is the largest amplitude recorded on the seismogram, independent of its time of arrival or period.

The ground motion recorded at the top of each mountain is considerably larger than that recorded at the base. The spectral ratios show that the topographic amplification is frequency-dependent, as would be

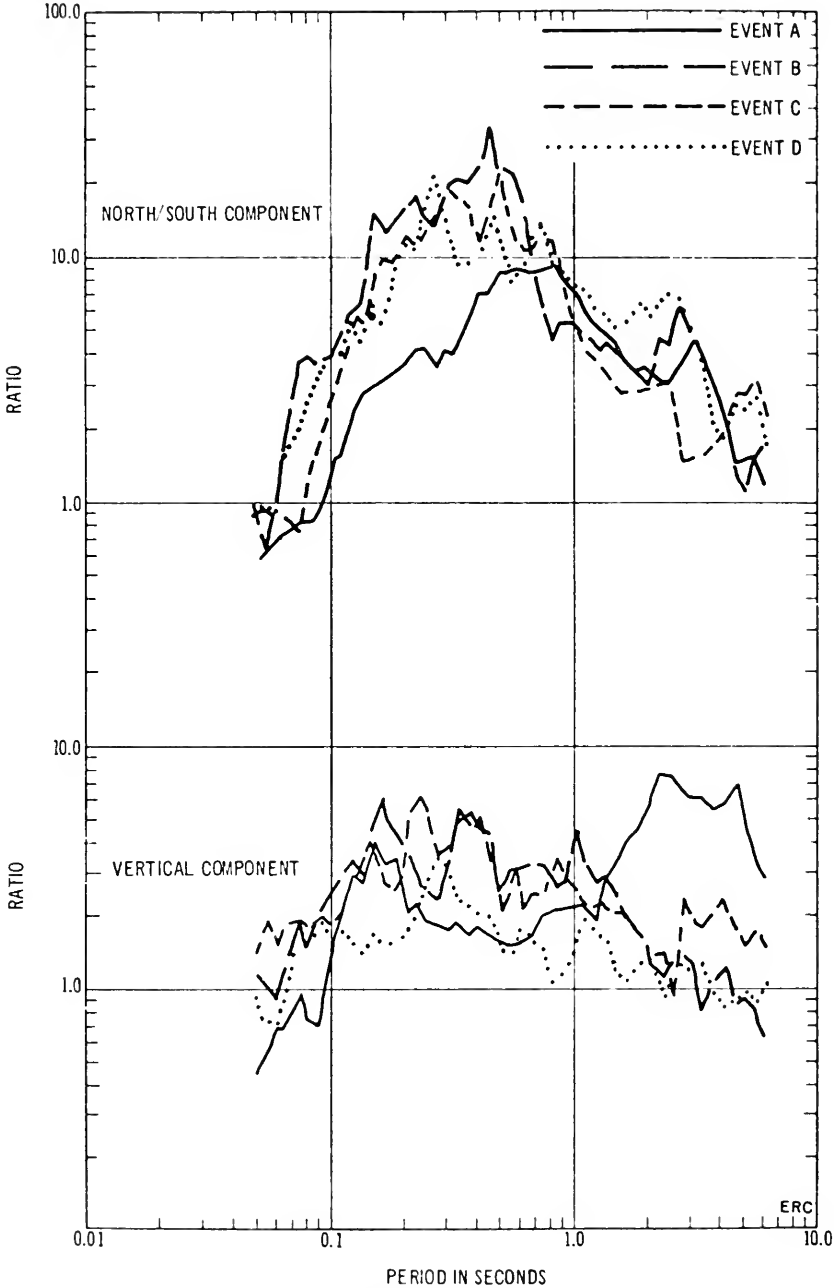


Figure 4. Ratios of PSRV spectra at Kagel Mountain (station 82, crest; station 83, base).

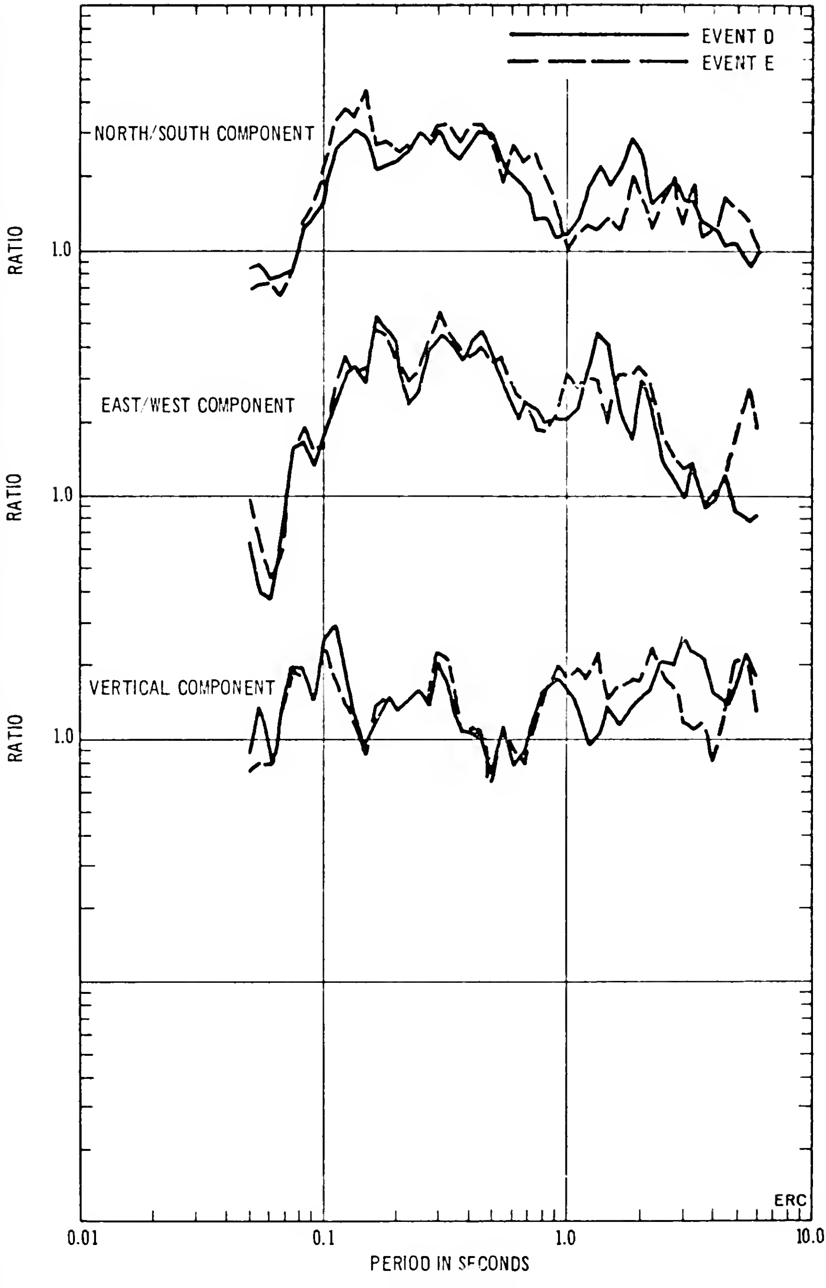


Figure 5. Ratios of PSRV spectra at Josephine Peak (station 80, crest; station 81, base).

Table 1. Ratios of maximum acceleration, velocity, and displacement amplitudes, Kagel Mountain and Josephine Peak.

Event	Component	Crest acceleration / Base acceleration	Crest velocity / Base velocity	Crest displacement / Base displacement
Kagel Mountain (Stations 82/83)				
A	North/south	1.14	2.20	3.15
	Vertical	1.02	1.26	2.87
	Resultant vector	1.03	1.57	2.96
B	North/south	1.41	3.64	7.95
	Vertical	1.09	1.60	3.52
	Resultant vector	1.07	2.45	6.13
C	North/south	1.75	3.96	5.70
	Vertical	2.31	2.65	1.91
	Resultant vector	1.46	2.84	3.80
D	North/south	1.58	4.08	5.97
	Vertical	0.64	0.97	1.29
	Resultant vector	0.76	1.86	6.01
Josephine Peak (Stations 80/81)				
D	North/south	0.83	1.80	2.03
	East/west	1.50	1.81	2.46
	Vertical	1.31	1.58	1.82
	Resultant vector	1.56	2.26	2.22
E	North/south	1.40	2.25	1.72
	East/west	1.56	2.28	2.24
	Vertical	1.28	1.80	1.83
	Resultant vector	1.63	2.54	1.94

expected. It is also evident that the manner in which the motions are amplified is different for each mountain; that is, the amount of amplification and the period ranges that are amplified are different. The mountains are different in size, although they are similar in shape (the ratio of the half width to the height is nearly constant—approximately 3½, an average slope of about 16°). Kagel Mountain is smaller than Josephine Peak, with a height of about 1400 feet and a half width of roughly 5000 feet. Josephine Peak has a height of 3500 feet and a half width of 12,000 feet. There is a very noticeable difference in the shape of the spectral-ratio curve with mountain size (see figures 4 and 5). At Kagel Mountain, the amplification occurs over a narrow range of periods. At the larger mountain, Josephine Peak, the spectral-ratio curve shows amplification over a very wide range of periods. Also, the peak spectral ratios were considerably greater than the peak amplitude ratios (particularly on Kagel Mountain and to a lesser degree at Josephine Peak). Since PSRV amplitudes are dependent on the duration (number of continuous cycles) of motion (Lane, 1972), this is an indication of longer signal duration at the tops of the mountains (longer duration is very noticeable on the Kagel Mountain seismograms—see figure 6). The longer duration could be caused by resonance of the mountain or could be the effects of body-wave reflection and refraction within the mountain.

Kagel Mountain

At Kagel Mountain the north/south component spectral amplitudes at the crest are more than 10 times greater than at the base for periods between 0.2 and 1.0 second and 20 to as much as 30 times greater at periods around 0.4 to 0.5 second (see figure 4). Ratios of the vertical-component spectra are less consistent than the horizontal north/south and generally show much less amplification.

Comparisons of the velocity seismograms recorded at the crest and base from Aftershock A are shown in figure 6. The seismometers were oriented in the north/south direction (transverse with respect to the direction to the epicenter). There is a very noticeable difference in the duration and amplitude of the shear waves. The shear waves on the crest exhibit many more cycles of motion and larger amplitudes than the base. It is possible that the mountain was excited at the resonant period by the shear-wave motion. Assuming a 10,000 ft/sec velocity for the shear waves and using a 0.5 second period (which is where peak amplification occurs), a wave length of 5000 feet is obtained, which coincides with the half width of Kagel Mountain. So it appears feasible for the shear waves to cause resonance, because the wave lengths are comparable to the dimensions of the mountain.

Peak velocity amplitudes at the crest are about 2 to 4 times larger than those at the base, but it can be seen (figure 6) that the later part of the shear wave arrival is many times larger at the crest than at the base. The amplification in the time domain in this part of the record is comparable to that seen in the frequency domain.

Josephine Peak

The Josephine Peak spectral-ratio data show amplification over a broader range of periods than was observed at Kagel Mountain. The ratios of the horizontal component PSRV spectra tend to peak at periods of about 0.15 second, 0.2 to 0.3 second, and 1.5 to 2.0 seconds. The amount of amplification is roughly the same at each of three period ranges and is a factor of about 3 for the north/south component and about 5 for the east/west component. As noted at Kagel Mountain, the ratios of the vertical components show less amplification than the horizontal components.

North/south component velocity seismograms recorded at the crest and at the base of Josephine Peak from Aftershock D are shown on figure 7. The north/south direction is approximately transverse with respect to the direction to the epicenter. It is seen that the amplitude at the crest is greater than at the base over much of the seismogram. The difference in peak velocity amplitudes is a factor of about 2. The distinct difference in shear-wave duration that was observed at Kagel Mountain is not noticeable at all at Josephine Peak. Evidently there was shear wave amplification, but the dimensions of the mountain relative to the incoming wave lengths were not closely enough matched to produce the type of amplification seen at Kagel Mountain. There is amplification in the longer period (1.5 to 2.0 seconds) range, which was not observed at the smaller mountain. This would be expected because the larger mountain should affect the longer periods.

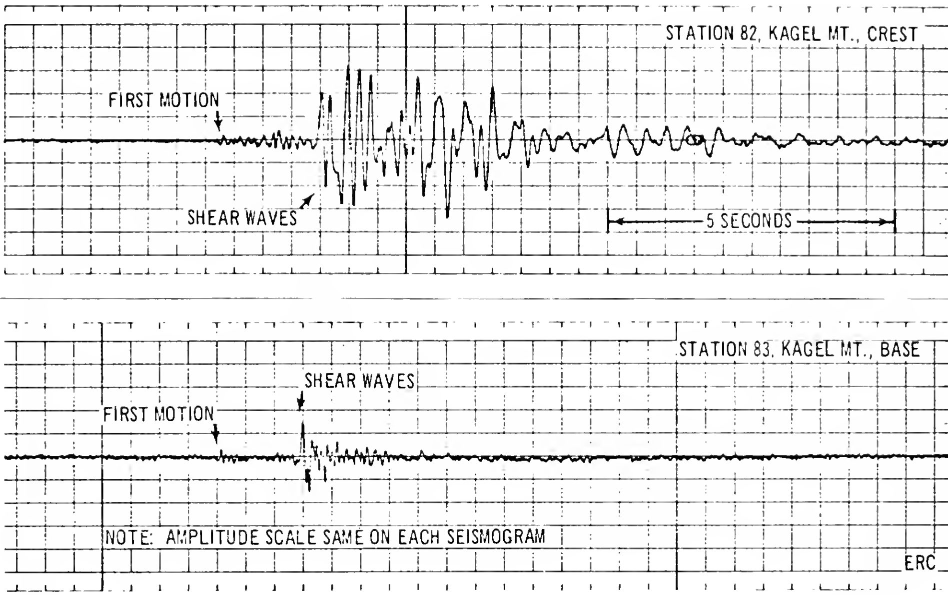


Figure 6. North/south component velocity seismograms recorded at the crest and the base of Kagel Mountain, Aftershock A.

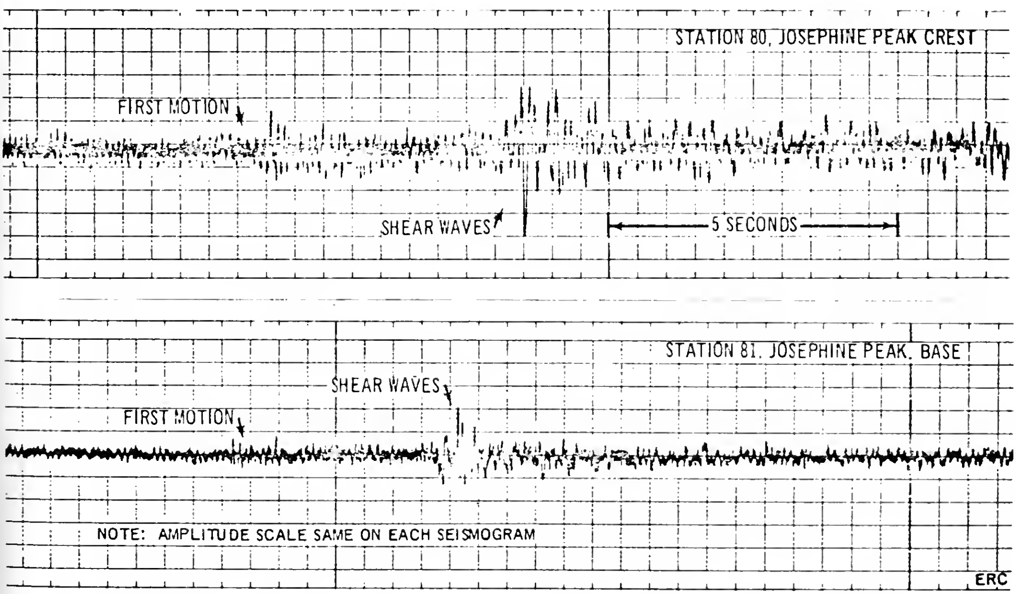


Figure 7. North/south component velocity seismograms recorded at the crest and the base of Josephine Peak, Aftershock D.

Again, assuming that the shear-wave velocity is around 10,000 ft/sec (which means the surface-wave velocity is roughly 9000 ft/sec), the wave length at a period of 1.5 seconds is 13,500 feet, which is about the half width of Josephine Peak (12,000 feet).

SUMMARY

The data collected at Kagel Mountain and Josephine Peak indicate that seismic signals can be significantly affected by topography. This observation is important in terms of the seismic safety of facilities built on topographic prominences. The widely accepted belief that structures built on hardrock are less susceptible to damaging ground motion than those on unconsolidated materials could be a misleading generalization; that is, selecting a hardrock site on a mountain rather than an alluvium site in a valley might not improve, and might even worsen, the seismic risk to the facility. The largest amplification of motion at the crests of these mountains (relative to the base) is as large or larger than the amplification normally caused by the presence of near-surface unconsolidated layers.

The amount of amplification and the periods at which it occurs vary with the size of the mountain and are probably a function of the relationship between the wave lengths of the incoming signal and the dimensions of the mountain. While there is some correlation noted between the amplification and the half width of the mountain, it is not clear that this dimension is necessarily the important one. Other dimensions, such as height, slope, general shape, etc., might also be important factors.

ACKNOWLEDGMENT

This work was performed for the Office of Effects Evaluation, Nevada Operations Office, U.S. Atomic Energy Commission, under Contract AT(29-2)-1163.

CHAPTER 24

Earthquake Risk in Relation to Earthquake Characteristics [1]

by Bruce A. Bolt [2]

MAGNITUDE AND INTENSITY

The San Fernando earthquake of February 9, 1971, is of considerable interest because of its unusually high intensity along the southern foothills of the San Gabriel Mountains and in the northern San Fernando Valley (see figure 1). The peak accelerations of the earthquake, recorded at Pacoima Dam, reached 1¼ g horizontally (Trifunic and Hudson, 1971). Accelerations greater than 0.2 g were measured at five sites within 30 km of the epicenter. In her paper, Scott (1971) assigned a maximum Modified Mercalli intensity of VIII–XI to the San Fernando and Sylmar regions. The Wood-Anderson seismographs of the Berkeley network gave a mean Richter magnitude of 6.48 ± 0.15 (Bolt and Gopalakrishnan, 1972). The high values for peak acceleration and intensity for an earthquake of this moderate magnitude, say 6.5, caused some surprise among experts.

In order to assess the strong ground motion involved in an earthquake, seismologists and engineers have long sought a usable empirical relationship between magnitude and maximum intensity. A number of empirical curves exist, but there are many exceptions and no agreed form.

In this earthquake, like that of April 18, 1906, the hazard to life and property had two major causes: ground shaking and gross ground displacement along the ruptured fault segments in the San Fernando Valley and surrounding hills. Secondary hazards were from landsliding and "avalanches".

After weighing the evidence, it seems to me that the amplitude of the ground shaking in parts of the meizoseismal area during this earthquake was about as extreme as one might expect in earthquakes of even greater magnitude. The magnitude of an earthquake can be misleading insofar as propensity to damage and risk to life is concerned; an earthquake model for risk evaluation more satisfactory than magnitude is as follows:

The magnitude of a shallow earthquake increases as the length of fault rupture associated with it increases. In other words, the larger the magnitude, the more extensive is the severe shaking along the fault zone. So far as intensity of shaking near the fault rupture is concerned, the crucial difference between a moderate and great magnitude earthquake is due to the longer duration of strong shaking in great earthquakes. The farther the fault rupture propagates, the longer the seismic waves which arrive at any site. As the wave train continues to pass, the frequency spectrum of ground motion at the site will shift toward low frequency. This is because the waves of higher frequency attenuate relatively quickly as the distance between site and moving rupture increases.

This model should be kept in mind when interpreting the field observations in this paper. It is consistent, incidentally, with the main effects of the California earthquake of April 18, 1906. The Report of the State Earthquake Investigation Commission shows a Rossi-Forel intensity of X (the highest on that scale) all along the ruptured San Andreas fault. As Louderback (1942) pointed out, however, this indicates only that the fault broke the surface; structures along the fault, such as ranch houses, were usually little damaged from shaking. With hindsight, this magnitude 8¼ earthquake can be said to have produced maximum Modified Mercalli intensity of IX at many places in the coastal region from San Benito County to Humboldt County; where soil properties were particularly unfavorable to shaking, intensity X may apply.

GROUND SHAKING

There was much damage from pure ground shaking in the San Fernando earthquake. From a field survey made of damaged houses in the meizoseismal area (Bolt, 1971) immediately following the earthquake, I conclude that ground vibrations (with damaging frequencies > 1c/s) were no more intense along the zone of thrust faulting in San Fernando than along the foothills of the San Gabriel Mountains in the vicinity of Olive View. Many wood-frame dwellings, for example, in both areas sustained little or no structural damage. Within the faulted zone in San Fernando, it was often difficult to disentangle shaking damage from that due to shifted foundations, which was, for many buildings, the more probable cause (photo 11). Certainly the rapid decrease in building damage within a block on each side of the fault offsets was striking, indicating that the shaking in the immediate vicinity of the fault was not as severe (see photos 4, 12) as in other parts of the meizoseismal region.

Unfortunately for research studies, some rock and soil foundation conditions were not represented in the meizoseismal region. For example, in the San Fernando city area, surficial soil and alluvium remained compacted; ground water played a rather minor role. Major water-associated features, such as liquefaction,

[1] Submitted for publication September 17, 1971.

[2] Director, Seismographic Station, University of California, Berkeley.

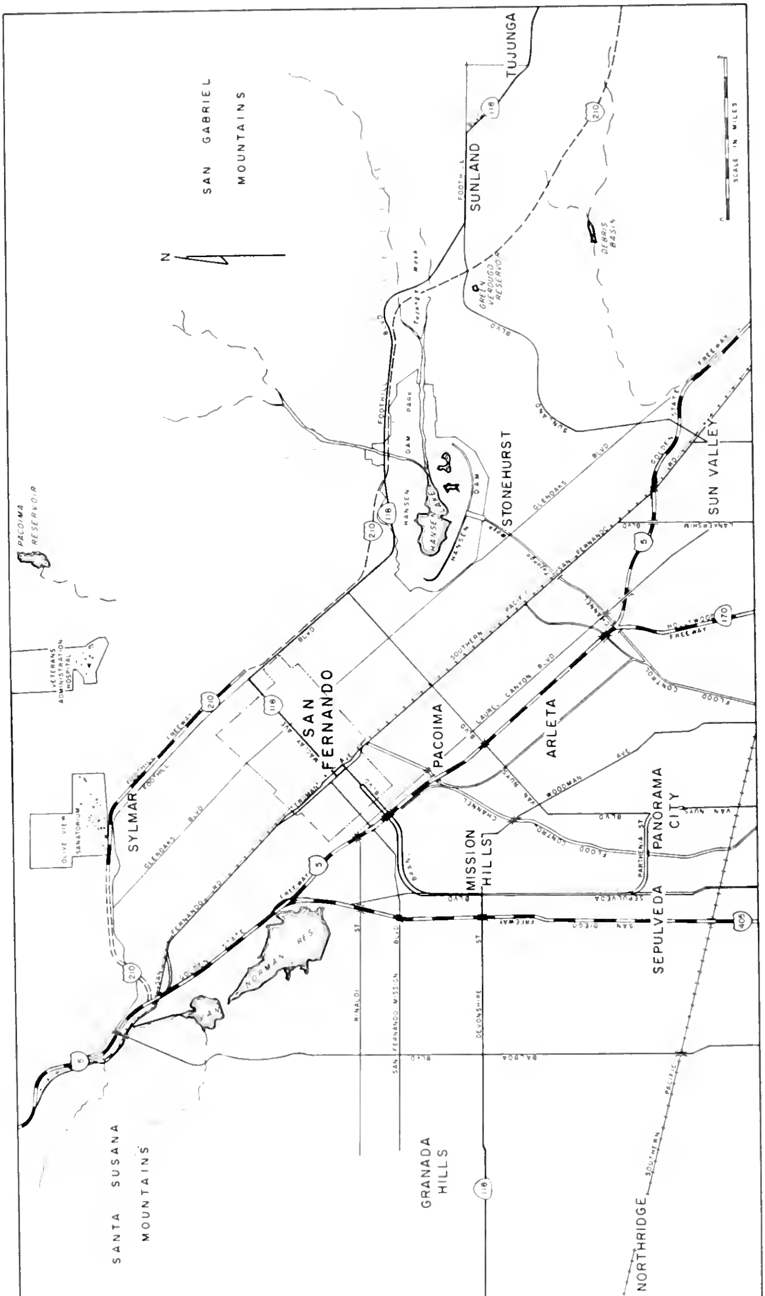


Figure 1. Index map of the San Fernando area. Surface faulting is shown in a general way by heavy lines. Area of most significant damage is shaded.

lurching, and differential settlement, were generally restricted to the area about Sylmar Juvenile Hall and Van Norman reservoirs.

By-and-large, the more modern dwellings withstood shaking without loss of life or structural damage. Wood-frame houses generally survived well throughout the area of strong shaking both in San Fernando and in Sylmar along the foothills. Some damaged houses were already deteriorated with age; dry rot and termites had left some older timber structures in a weak condition. Some wood-frame houses not in the fault zone shifted on or off their foundations.

The strong ground shaking caused unusual damage to one particular design of split-level house, particularly those in the new housing developments of the upper Sylmar area.

Photo 1 shows one such house. The garage has collapsed, pulling the second story away from the first story. The large door area in the garage front had replaced shear bracing such as is common in other types of two-story dwellings. Adequate shear bracing and tiedowns must be provided even if there are large openings in the structure. The type of sheathing on garage walls in these houses gave little shear strength.

Some older brick homes collapsed while others of reinforced masonry performed well. In several places, reinforced block construction, usually one or two stories in height, survived the shaking without damage (see photo 8).

Photo 2 shows the backyard of a particularly well-built modern brick house in the faulted zone of San Fernando. The damage from shaking appeared minor, although loose objects inside the house were thrown down. As may be seen in photo 2, the light roof of the patio collapsed and the air conditioner toppled but chimney and swimming pool were intact. An unusual hazard to life was noted here: the severe vibrations caused water to overtop the pool and inundate a basement room which was used as a bedroom. Fortunately the occupant scrambled to safety in the darkness.

While the brick house was not much damaged by shaking, it sustained major structural fractures from the faulting of the ground beneath. One side had broken away from the other and dropped several cms. A wood-frame house would probably be easier to repair.

FAULTING

The earthquake was associated with major thrust faulting (photo 3) along the edge of the San Gabriel Mountains and in the valley floor, which broke the ground surface more or less continuously for at least 15 km. Although the ground breakage was complex in places, the principal strike was nearly east; the dip was 35° to 55° to the north (Bonilla et al., 1971).

In recent years great emphasis has been placed by some people on hazard to structures built straddling fault zones. Because little damage has occurred historically in this way, the ground breakage through the single-family dwellings of San Fernando provides an opportunity to examine the matter.

In the flat-lying San Fernando area, even in the zone of greatest ground displacement (about 1 m vertically and 1 m laterally), no substantial wood-frame

Photo 1. New split-level dwelling in the housing development southeast of Olive View Hospital. Garage under two-story level has collapsed (note crushed car).

Photo 2. Well-constructed modern brick house on Warren Street, Sylmar. This dwelling was in the Sylmar zone of tectonic ruptures. Water sloshed out of swimming pool and inundated a basement room where a boy was sleeping.

houses collapsed. No loss of life and few serious injuries resulted from this extraordinary ground motion. For example, the little-damaged house in photo 4 was right on the fault scarp.

On the other side of the coin, there was much structural damage in the Sylmar segment of the San Fernando fault zone because of the fault thrust. Dozens of houses in the area, although still standing after the earthquake, had to be demolished; and many more required expensive repairs. It is a tragedy that no scheme of insurance for geological hazards has yet been worked out which gives reasonable coverage for dwelling damage to all citizens.

Photo 3. Fault scarp about 0.4 m high across dirt road in a farm field. One of a series of five parallel scarps with total vertical motion of about 0.8 m north of Van Nuys Boulevard along the foot of the hills. View to north. No lateral displacement.

Photo 4. Undamaged wood-frame home on Foothill Boulevard in Sylmar fault zone. East view. Edge of thrust zone runs a few feet from the house across the lawn.

In considerations of seismic risk, this earthquake gives an illustration of extensive tectonic ground breakage in a region where no fault was drawn on the available geologic maps. There had been indirect evidence, mainly based on ground water levels, of possible faults under the surface of the valley alluvium (Oakeshott, 1958). For some unknown mechanical reason, the mapped thrusts along the base of the San Gabriel Mountains, such as the Grapevine, Hospital, and Lopez faults, showed no surface displacement after this earthquake.

In contrast with purely strike-slip faulting, such as on the San Andreas in 1906, when little en echelon faulting accompanied the main break, the thrusting in San Fernando produced a fractured zone up to 200 m wide in places. Compression produced specialized and often spectacular damage, for example, to water and gas mains (photo 14). Effects of the thrusting were often transferred into a wider area by the works of man. Such transfer of displacement is shown in photo 5 taken on Orange Grove Avenue, San Fernando, on the day of the earthquake. The concrete slab has been ejected from the space between the slabs below it after shortening of the whole city block by 1.7 m. A corresponding piece of ejected curbing was found at the other end of the block.

THE SYLMAR GROUND BREAKAGE

In the map, figure 1, a zone stretching from east of Balboa Boulevard across the north end of Upper Van Norman reservoir and Highway 5 to Sylmar Juvenile Hall is distinguished by broken lines. The extreme damage in this area was somewhat different from that in San Fernando. There were many gravitational slides, particularly in the filled land. A shallow ground

Photo 5. Ejected slab in sidewalk at corner of Orange Grove and Phillippi in Sylmar fault zone. Fault thrusting caused by shortening of continuous sidewalk along block by about 2 m.

water table (less than 2 m down) permitted the seismic shaking to produce soil liquefaction phenomena: slumping, lurching, sand boils (see Youd, 1971).

My original impression after a rapid field study was that there was also evidence of tectonic thrust faulting with some left-lateral displacement under this zone. Some of this evidence is as follows: First, there was a linear zone of ground breakage running through the Juvenile facility across Highway 5 and Sepulveda Boulevard through Sylmar Converter Station across the top of Van Norman reservoir. Left-lateral displacement of about 0.5 m could be seen clearly along Sepulveda Boulevard and along a concrete canal parallel to it (photo 6). Secondly, the east-west zone of

Photo 6. Left-lateral displacement in concrete culvert (view northwest) parallel to Sylmar Converter Station and Sepulveda Road. Produced either by underlying tectonic displacement on the Mission Hills fault or by an extensive landslide.

breakage could be traced westwards into the new housing developments along the foothills north of Balboa Boulevard (see photo 7). The zone was intermittent, and ground breakage varied in character and direction with many definite gravitational slides. Thirdly, the zone of surficial ruptures was concentrated along the known east-west tectonic features, the Olive View fault and the Mission Hills syncline (see Oakeshott, 1958). There is thus circumstantial evidence for underlying tectonic displacement.

Photo 7. Damage to concrete block retaining walls, sidewalk, and gutter along Balboa Boulevard (west side).

An interpretation in terms of primary tectonic dislocation has not been accepted by a number of geologists. Youd (1971), for example, prefers to interpret the surface fissures completely in terms of a large landslide with head along the margin of the hills and toe in the floor of the Van Norman reservoirs. This model shows slippage on a liquefied layer of sandy loam along a gentle slope of less than 3°. One reason that Youd chose this interpretation is that there is change from left-lateral to right-lateral slip from the southern to the northern part of the disturbed zone along Sepulveda Boulevard. His model fails to explain left-lateral displacements northeast of Juvenile Hall, greater compression of Southern Pacific rail tracks across the zone than of the underlying embankment, and compressional damage and fissuring west of Balboa Boulevard. The elastic-rebound theory predicts that greater permanent crustal displacements will occur in the zone of faulting than some distance away.

My preferred model is that some thrusting and left-lateral displacement occurred at depth along, and to the south of, the Olive View fault. The surface expression of this primary motion was complicated and obscured by considerable gravitational sliding made possible by decreased shear strength of wet, near-surface sandy soils. The pattern of aftershocks, which has a high level of activity north-south through the region of the Highway 5 interchange, gives a little support for this model.

ADEQUACY OF BUILDING CODES

An important lesson from this earthquake is that significant changes in structural design take place so gradually over the years that the consequences to seismic risk may not be recognized.

Clear examples concern masonry, the modern design of single-family wood-frame houses and the use of reinforced concrete in massive structures. This earthquake demonstrated that well-constructed concrete block structures, unlike much older brick masonry, have high seismic resistance (photo 8). Of course, if built straddling tectonic ruptures, even modern masonry may be heavily fractured, as were the concrete pavements across the thrusts in San Fernando.

As already mentioned, some modern wood-frame houses, presumably built to code, collapsed in this earthquake. In most cases, unlike in the older type of house with relatively small windows and separate garage, there was a lack of shear bracing provided in the walls on the ground level (usually the garage—see photo 1). The following list contains a number of points which it would be prudent to incorporate in the design and upkeep of wood-frame houses to minimize seismic damage.

(a) Exterior sheathing should be waterproof plywood of $\frac{5}{16}$ inch minimum thickness adequately nailed. Because garage doors and large windows present special hazards, such additional internal bracing as plywood sheathing should be used.

(b) Internal lighting fixtures and utility equipment (water heaters, refrigerators, wall stoves) should be fastened to structural elements securely enough to withstand accelerations in excess of 0.5 g (photo 9).

(c) Masonry chimneys should be adequately reinforced and braced to structural elements to prevent collapse into the living area (photo 10), or lightweight flues should be used. Reinforcing using 4 rods of vertical steel does not provide sufficient safety in high earthquake-risk zones.

(d) The frame and sill plates should be inspected periodically to assure that the wood structure built to resist lateral forces and tied to concrete foundations has not been damaged by termites or fungus.

(e) Since concrete-block walls in gardens often collapse during seismic shaking, all concrete-block walls should be tied to adequate footings.

Photo 8. Contrast in response of masonry to seismic shaking. First Street in downtown San Fernando about 3 km south of Sylmar fault zone. A child was killed in the older structure.

Photo 9. Frame distortion and interior damage in two-story wood-frame house on Orange Grove Avenue, San Fernando, within fault zone. Foundations moved considerably, but no injuries resulted.

Finally, the failure of the psychiatric ward at Olive View Hospital and the heavy damage of the main facility is a very disturbing commentary on the adequacy of building codes. The thrust mechanism of this earthquake, which had greater vertical accelerations than any previously recorded in California, probably was a factor in causing the great amount of damage. A committee of the Structural Engineers Association of Southern California has given its opinion "that the lateral-force design of the two structures generally complied with the building codes in existence at the time. Failures in both units occurred in columns due to increases in vertical loads as a result of vertical accelerations of the ground and high lateral accelerations causing severe shear and bending stresses."

The Olive View buildings were reinforced concrete; it would appear that evaluation of the design of reinforced concrete structures is subject to considerable uncertainty at the present time. The need for continuous reworking of earthquake design codes suggests that, while the members of the engineering profession must take a central place in such considerations, it would be advantageous to associate seismologists, geologists, and other interested professionals.

SITE EVALUATION

Study of the earthquake emphasizes the great importance of adequate site evaluation for structures in an earthquake-prone area. The concept is familiar to a small number of seismologists, engineers, geologists, and planners; but there is a need to have it accepted more widely.

Photo 10. Unreinforced chimney which fell through roof of dwelling in San Fernando.

For many years, the Atomic Energy Commission has required the sites of proposed nuclear power reactors to be evaluated thoroughly for seismic hazards (Fischer and Murphy, 1970). Consultants from the disciplines of geology, seismology, soils engineering, and structural engineering carry out the assessment.

There are two main situations. First, for major structures with a high level of human occupancy or with long life expectation in regions where great earthquakes have occurred and the seismicity is high, there is no need to introduce the detailed probability aspects of earthquake occurrence. The assumption can be made from the outset that the structure must sustain without danger of collapse the greatest earthquake intensity mechanically feasible at the site. From a study of the historical seismicity, a seismologist can estimate this maximum intensity of shaking on firm ground near the site. After allowance for any modification of the intensity at the actual site by the soils, the ground acceleration can then be estimated. Specification of acceleration levels as a function of frequency and the duration of strong shaking define a design earthquake for the site in question.

The second situation arises when large earthquakes are known historically but are very infrequent. Assessment of site response alone is no longer sufficient. In terms of probability, there is low seismic risk because the time between damaging earthquakes is very long. (In the case of the St. Lawrence Seaway, perhaps several centuries.) The analysis requires a treatment in terms of probability. For example, if a return period of one hundred years is selected as tolerable to the owner, community, and users, then the design earthquake would have as its peak acceleration that which might be expected of an earthquake with a probability of one in one hundred years. Of course, economic and social factors, as well as building use, will change the acceptable odds.

The Veterans' Administration faces both situations described above. Its hospitals, of many designs and ages, are located in many states, each in a different tectonic environment. After the tragic collapse of some of the hospital buildings at Sylmar during the February earthquake, the Administration took action to study the overall situation (see Bolt, 1971b). A special "Earthquake and Wind Forces Committee"* was set up in April 1971. The principal objectives were to review and revise building codes for future VA design and to prepare guidelines for the estimation of risk for present hospitals. Site evaluation is clearly of critical importance in both cases.

ASSESSMENT OF INTENSITY IN THE FAULTED AREA

From the field study that began on the morning of the earthquake, Dr. Robin Adams, who is familiar with intensity assessments in New Zealand, and I concluded that the highest Modified Mercalli intensity reached in San Fernando was IX with a few restricted areas of X in Sylmar.

Photo 11. Day of the earthquake, looking east along thrust zone across Orange Grove Avenue, San Fernando. Wood-frame house straddles faulting in street and curbing. Note chimney, air conditioner, and TV antenna in place.

To recapitulate, grade IX: "General panic. Masonry** D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations.) Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas, sand and mud ejected, earthquake fountains, and craters."

It is difficult to find any area of the meizoseismal zone in which this description was exceeded. Even in the zone of severe thrust faulting in San Fernando, many wood-frame houses survived in quite surprising fashion (photo 11—note antennas and chimney standing). Thrust fault movement was responsible for severe damage to pavements in a narrow zone, yet structures nearby had little damage to foundations and little racking of frames (photo 12). There are, of course, more complexities of damage and felt reports than are covered by the present Modified Mercalli scale; this leads to marked differences in assessing the intensity level. The variation in description between

* Members were B.A. Bolt, R.G. Johnston, James Lefter, and Mete A. Sozen.

** Masonry B: reinforced but not specially designed; Masonry C: ordinary mortar and work; Masonry D: weak shear strength, indifferent workmanship.

Photo 12. Adelphia Street in fault zone, San Fernando, view southeast. Spectacular left-lateral displacement of curbing accompanied by compression of driveway.

grades IX and X, given the present building conditions, makes selection difficult. The matter would not be important except that prediction of acceleration in future earthquakes often hinges on such selections. The time is overdue for a careful reconstruction of the Mercalli Scale as used in California. A study group from the relevant disciplines should review the present scale in the light of recent California earthquakes and damage to various types of structures.

There were variations in intensity over short distances in this earthquake. For example, damage to homes in San Fernando within a block of the thrust faulting was much less than one might expect. Near the Pacoima Dam, where accelerations exceeding 1 g were recorded, the brick chimney at the caretaker's cottage did not fall!

Mrs. Scott (1971) tentatively assigned maximum intensity up to XI to a small area of the San Fernando foothills. This assignment was based upon (a) failure of the Veterans' Administration hospital and the Olive View hospital at Sylmar, (b) major damage to the Van Norman Dam, (c) severe damage to water and power facilities, (d) collapse of freeway overcrossings, (e) major ground rupture, and (f) bending of railroad tracks. Grade X would appear to cover (a), (b), (c), (d), and (e) adequately. Grade XI has a short and limited definition: "Rails bent greatly. Underground pipelines completely out of service." Of the many miles of railroad track in the meizoseismal area, there was great distortion only in a few hundred m (for example, across the Sylmar Juvenile Hall ground rupture).

SOCIAL BEHAVIOR

On our field inspection in San Fernando and Sylmar after the earthquake, Dr. Adams and I were continually impressed by the generally calm response of the population. Many people with severely damaged homes moved out to the front lawns and sat there during the day (see photos 11 and 12). During the warm night of February 9, many residents slept on the lawns and in cars. Aftershocks caused concern; there were reports later of children being disturbed in behavior by the continuing shaking.

A major contribution to the excellent community reaction was the availability of transistor radios in almost every home. Despite failure of the electrical system, there was never a time in which the population was not aware of the general situation. Radio stations devoted much of February 9 to discussions of the earthquake and the way in which problems were being met.

The lack of water proved to be not too much of a problem. People now usually have a good reserve of drinkable materials stored and in refrigerators. The request for the people to stay out of the damaged area seemed to be generally followed on the morning of the earthquake. There was very little activity on the roads throughout the area. One could drive with considerable ease through San Fernando. It was not until some days later that sightseers started to come. They were not greeted with very much warmth.

The experience of this earthquake reinforced the need to maintain certain basic equipment in homes in earthquake areas: portable fire extinguishers, a first aid kit, and a transistor radio.

TYPE OF EARTHQUAKE IN RELATION TO HAZARD

Loss in the San Fernando earthquake emphasized the need for a more sophisticated conception of earthquake risk. Historical world-wide evidence using earthquake effects indicated previously that earthquake mechanisms play an important role in the pattern of ground shaking. Theoretical seismological models were defined which included this concept (see Bolt, 1970, p. 14); but no detailed quantitative predictions of intensity as functions of distance, fault type, and geology have yet been worked out. Earthquakes associated with transcurrent rupture of the San Andreas fault, such as the April 18, 1906, earthquake and the Imperial Valley 1940 shock, should not be used to develop universal models of ground shaking and intensity.

In the 1952 Kern County earthquakes, both left-lateral and reverse dip-slip motion occurred on the White Wolf fault. In the 1971 San Fernando earthquake, the San Gabriel Mountains were thrust to the south over the valley. Faulting dynamics with a substantial vertical component of slip lead to special ground response of both theoretical and practical importance. Along the San Fernando thrust fault zone, the breadth of the broken ground due to the faulting was generally greater than along much of the 1906 San Andreas transcurrent rupture. In many places en echelon fissures developed in the 1971 faulting over a 200 m wide belt. Thrusting and left-lateral offsets caused up-buckling and rotation of the ground. This vertical distortion led to particularly serious dislocations in road pavements (photo 13) with attendant increase of risk from lack of access. Tectonic compression caused severe damage to underground utility systems (photo 14).

Finally, the thrusting mechanism produced a different frequency spectrum of ground shaking than previously noted. Instrumental measurements at Pa-

Photo 13. Dislocated roadbed, view southeast along new Freeway 210 (west lane) near Maclay Avenue. Both overthrusting and left-lateral offset occur in line with the San Fernando fault zone.

Photo 14. Compressed section of gas pipe removed from the main line across the thrust faulting near Glenoaks Boulevard, San Fernando. Note ejected concrete curb.

coima Dam, for example, on the southern edge of the upthrust block show peak vertical accelerations of 0.8 g. This relatively high *vertical* acceleration is consistent with the type of damage to such buildings as Olive View Hospital. Concrete columns there punched through the concrete basement roof. Sustained vertical accelerations, on the other hand, are not likely to produce as spectacular failures as lateral shaking in structures with small shear strength. Thus, the vertical portion of the shaking in the San Fernando and Sylmar region, while felt strongly, was absorbed without much damage to trees, utility poles, chimneys, roof fixtures, or wooden frames.

ACKNOWLEDGMENTS

My thanks to Dr. P. Byerly, Mr. W. Cloud and Mr. R. Miller for comments on the manuscript. Professor George Simonds suggested some lessons for homeowners on seismic resistance and safety. A number of the photographs are to be credited to Dr. R. D. Adams, who studied the earthquake effects with me.

Section 3

Damage

CHAPTER 25

Building Damage in San Fernando Valley [1]

by Karl V. Steinbrugge,[2] Eugene E. Schader,[3] Donald F. Moran [4]

ABSTRACT

Objectives of this paper are to review the most important building-damage information and to analyze relationships of damage to soils and geology.

The Los Angeles County Coroner's Office reported 58 deaths directly attributable to the February 9 earthquake out of a current population of 7,032,000. Total loss to buildings and structures has been estimated at $511,000,000.

Highest acceleration ever recorded in an earthquake was recorded at Pacoima Dam during this earthquake. The fracturing of the rock during the earthquake and the instrument's location on an outcrop of crystalline rock at the dam may have significantly influenced the recording with respect to unfractured rock. Duration of strong motion was about 12 seconds.

The number of buildings astride the fault trace were few compared to the total number of buildings in the vicinity, but those on the trace were severely damaged.

About 25 percent of all dwellings in the hardest-hit area had losses over 5 percent of value. This represents 1 percent of all the dwellings in the San Fernando Valley considered in this study. There was no noticeable difference between the performance of concrete-slab floors and wood-joist floors. One-story dwellings performed substantially better than two-story dwellings and much better than combination one-and-two-story dwellings. Modern dwellings performed better than older ones. Calculated average loss for all dwellings is 6.6 percent. Steel-frame and reinforced-concrete highrise buildings generally performed well.

Two zones of higher-than-average dwelling damage exist: one contiguous with the zone of faulting in the valley, and the other along the base of the San Gabriel Mountains. There may be a relationship between the alluvial soils and sedimentary strata and the firmer rock of the foothills.

Detailed instrumental and theoretical studies of the dynamic properties of soils and stratified sedimentary formations, particularly varying thickness of alluvial materials on irregular bedrock surfaces, must be given high research priority.

The objectives of this paper are to review the most important building damage information gathered by the authors and their analysis of it and to analyze the geographic distribution of damage in order to determine the relationship of damage to surficial soils and geology.

One of the two principal resources used is the insurance-oriented report "San Fernando Earthquake, February 9, 1971", by Steinbrugge, Schader, Bigglestone, and Weers, and its back-up information; major condensations of it are included in this study. The second resource consisted of the substantial amount of information made available from the forthcoming definitive engineering volumes being prepared by the Earthquake Engineering Research Institute (EERI) in cooperation with the National Oceanic and Atmospheric Administration (NOAA), Department of Commerce. Both these publications will be very useful for persons wishing to study the more detailed data upon which this paper is based, since we cannot here discuss damage to numerous important structures and structural types, such as the Sylmar Converter Station, Sylmar Juvenile Hall facilities, and older non-earthquake-resistive brick buildings.

The Area of Heaviest Shaking

The region that was most heavily shaken is in the northern suburbs of the city of Los Angeles and in the adjacent small communities. Figure 1 shows the distance between the earthquake's epicenter and the population centers.

For the purposes of this report, the heavily shaken area of San Fernando Valley is defined by the outer geographic boundaries shown in figure 2, although the discussion of damage will include other areas. The northern limits are bounded by the base of the San Gabriel Mountains. However, there were areas of moderate damage to newer structures north of this limit near Solemint Junction, Newhall, and Saugus. Southern limits are bounded by the Santa Monica Mountains and by the Los Angeles River at the foot of the mountains. The eastern limits generally follow the Verdugo Mountains, part of the San Gabriel range. The western limits are the topographic changes in elevation of the Santa Susana Mountains and the Simi Hills.

The Valley is now primarily a residential area as agriculture has been phased out. Businesses serving the communities are concentrated along the major thoroughfares. Light industrial construction has grown in the post-World War II period. Most manufacturing plants are located along the two railroads.

[1] Manuscript submitted for publication November 9, 1971.

[2] Professor of Structural Design, University of California, Berkeley, California; Member, State Mining and Geology Board, State of California.

[3] Civil Engineer, Insurance Services Office, Los Angeles, California.

[4] Consulting Structural Engineer, Los Angeles, California; Chairman, NOAA/EERI San Fernando Earthquake Investigation Committee.

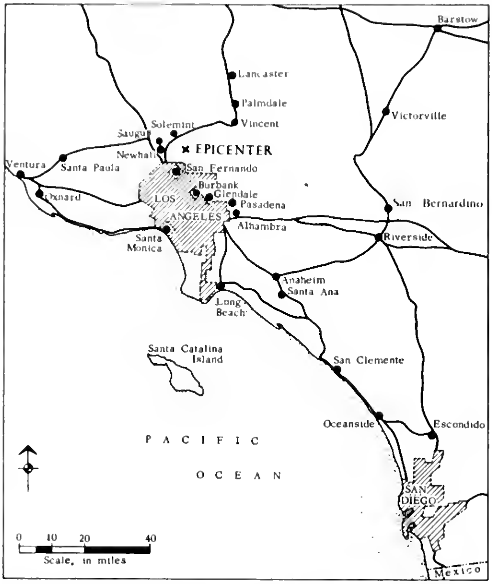


Figure 1. Map showing epicenter of the San Fernando earthquake and its relationship to southern California cities.

The City of San Fernando, incorporated in 1911, is an enclave within the City of Los Angeles. San Fernando's one principal business district, which is along San Fernando Road (formerly Porter Avenue), has brick masonry construction of the old buildings very much in evidence. The brick structures, built prior to the earthquake-resistant design requirements of the present building codes, used the poor quality sand-lime mortar that was standard at the time. Buildings for several blocks along Maclay Avenue northeast of San Fernando Road also represent the earlier period of the city. The older dwellings that surround this early business district were those that, in general, were the most severely damaged by the earthquake.

Mission San Fernando Rey de España, seventeenth in the chain of California missions, is in the city of Los Angeles and slightly beyond the southern limits of the City of San Fernando. Built originally in 1806, the mission chapel was first damaged by the 1812 earthquake. The February 9, 1971, earthquake severely damaged the thick adobe-walled chapel (photo 1) of the Mission and cracked the white-washed arches of the Convento Building along Mission Boulevard. The fate of the chapel has not yet been decided; however, efforts to reinforce the Convento Building are underway. Although damaged, the Mission stood slightly more than 1 mile from the heavily damaged Lower San Fernando Dam and about half a mile from the severely damaged Holy Cross Hospital without collapsing.

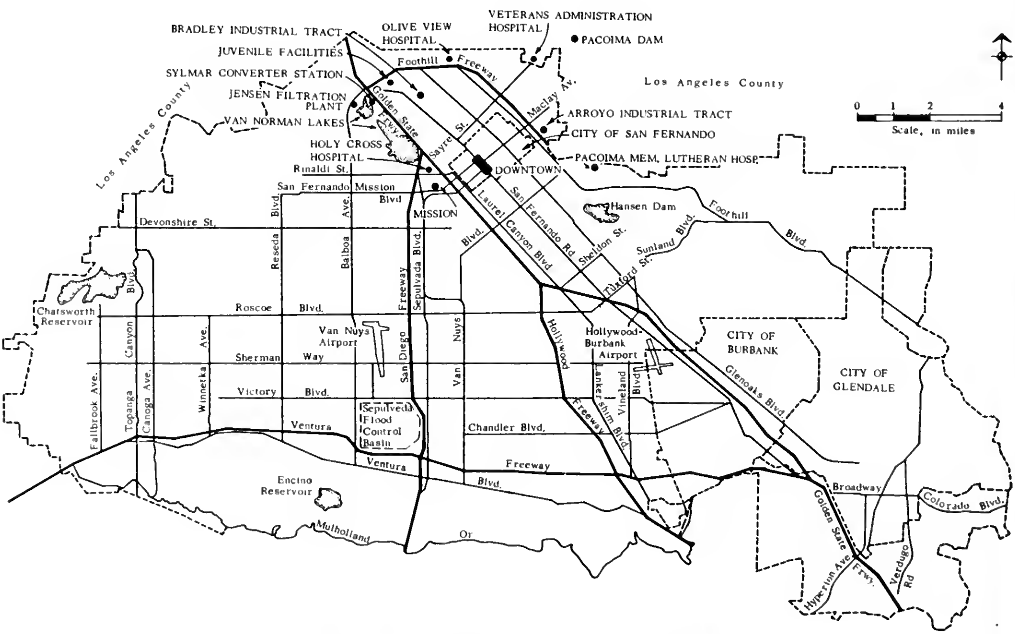


Figure 2. Area of San Fernando Valley that was heavily shaken.

Photo 1. Photo showing damage to non-reinforced adobe walls in the interior of the chapel of San Fernando Mission, originally built in about 1806.

Most of the other dwellings within the valley are post-World War II. Construction is mainly wood frame and stucco with some brick and stone veneer on the front lower half of some dwellings. Dwellings throughout the valley showed minor interior cracking, mostly in the older plastered interiors. Also, chimneys made of brick and unreinforced concrete in some of the older buildings were broken.

The heavily hit area of San Fernando Valley had a population of 1,284,200 in 1970 within the 289 square miles outlined in figure 2. If we include the duplex units as one-unit structures, 302,619 dwellings (one-unit structures) exist within the area outlined.

Life Loss and Injuries

The Los Angeles County Coroner's Office reported 58 deaths (table 1) directly attributable to the February 9 earthquake out of a current population of 7,032,000. The collapses at the Veterans Administration Hospital in the foothills of San Fernando Valley immediately claimed 41 lives; six died later as a result of injuries sustained. This was the largest life loss at one location incident to the earthquake. Three deaths occurred at Olive View Hospital; one due to falling building materials and two when life-supporting power supplies failed. One person died in the roof collapse of the old brick masonry Midnight Mission (a charitable facility) in downtown Los Angeles. If the shock had occurred minutes before when the upper dormitory area was fully occupied, the death toll would have been greatly increased. The person who died had left the building but was standing in front of it. A collapsing freeway bridge killed two men when their truck was crushed under a fallen span in the heavily shaken area of San Fernando Valley. One person died from injuries resulting in a fall from the freeway. Four deaths occurred in dwellings. Heart attacks reportedly took nine lives; however, the County Coroner's report does not list these.

Table 1. Life loss.
From Los Angeles County Coroner's records

Olive View Hospital		3
Patients	2	
Employees	1	
San Fernando Veterans Administration Hospital		41
Patients	31	
Employees	10	
Victims from Veterans Administration Hospital whose deaths occurred at other hospitals		6
Deaths from residences		4
Deaths from collapse of freeway overpass		2
Death in fall from freeway overpass		1
Death from collapsing wall		1
TOTAL		58

NOTE: Deaths from reported heart attacks or natural causes attributed to the earthquake are not included.

Information on injuries and other earthquake-related emergency cases was compiled by the Hospital Council of Southern California. The information in this paragraph and in table 2 is based on their compilation from replies received from 127 hospitals. In addition, the Red Cross treated the minor injuries of more than 3000 persons.

Table 2. Injuries and related problems.
From Hospital Council of Southern California records

Date	Outpatients treated	Inpatients admitted	Total
Feb. 9	1,524	161	1,685
Feb. 10	437	30	467
Feb. 11	367	24	391
TOTALS	2,328	215	2,543

Outpatient injuries or problems		Inpatient sick or injured, excluding transfers	
Lacerations	44%	Fractures	26%
Fractures or related	18%	Cardiac	19%
Emotional reaction	9%	Head injuries	12%
Contusions	8%	Psychiatric	12%
Cardiac	6%	Burns	7%
Remainder	15%	Remainder	24%

Dollar Losses

The total loss to buildings and structures, excluding land and building contents, has been estimated by the authors at $511 million; a breakdown of this value is given in table 3. The quality of the $511 million estimate is only fair, and probably it is on the low side.

Undoubtedly, incompatible data exist in the back-up material for table 3. Value can be based on replacement value, current market value, or assessed value, among others. Loss can be insured loss (a dollar deductible may have been applied before the loss was paid), loss as defined by the cost to bring the structure back to its original (not new) condition, and loss as defined by actual repair costs, among others. These variables in definitions, plus political and emotional

Table 3. Summary of earthquake loss.

	Dollar loss	*Reference*
Private Sector:		
Buildings, excluding land and contents		
Los Angeles City	$154,000,000	Table 4
San Fernando City	36,000,000	Table 5
Elsewhere	15,000,000	Table 5
Non-building structures, excluding land	35,000,000	Authors' est.
Public Sector:		
Los Angeles City	180,000,000	*O.E.P.
San Fernando City	34,000,000	O.E.P.
Los Angeles unincorporated	13,000,000	O.E.P.
Other cities	24,000,000	O.E.P.
Porter Ranch (aftershock damage)	8,000,000	O.E.P.
Utilities	12,000,000	O.E.P.
Total	$511,000,000	

* Office of Emergency Preparedness, Executive Office of the President.

considerations, can lead to inconsistencies when unqualified data are compiled from many sources.

Tables 4 and 5 state the losses to privately owned properties in the various cities and other jurisdictions throughout the damaged areas. Some of the dollar loss estimates may be crude guesses by local authorities.

Detailed information on losses to dwellings, high-rise buildings, and light industrial buildings is given elsewhere in this paper.

EARTHQUAKE FORCES AND EARTHQUAKE-BRACING SYSTEMS

Earthquake Forces

Strong-motion accelerographs recorded the earthquake forces at numerous locations throughout the metropolitan Los Angeles area; this subject is well covered by other authors in companion papers. However, the significance of the recordings relating to the observed damage in the most heavily shaken area and their significance relating to building code requirements are discussed here.

Horizontal accelerations. The closest strong-motion instrument to the epicentral region was at Pacoima Dam, northeast 1.5 miles from point "C" in figure 3 and also shown in figure 2. The horizontal ac-

Table 4. Los Angeles city damage.

From Los Angeles Department of Building and Safety, as of June 28, 1971

	Units	*Buildings*	*Estimated dollar loss*
Unsafe for human occupancy—posted "unsafe":			
Single family dwellings	0	522	$13,100,000
Apartments	1,149	54	11,500,000
Non-residential commercial and industrial	0	190	19,000,000
Major and moderate damage—remaining occupied:			
Single family dwellings	0	2,469	24,700,000
Apartments	0	192	7,700,000
Non-residential commercial and industrial	0	883	17,700,000
Minor damage:			
Single family dwellings	0	13,711	6,900,000
Apartments	0	1,748	17,500,000
Non-residential commercial and industrial	0	5,698	5,700,000
Other damage (estimated):			
Unreported damage	0	0	30,000,000
Personal property and inventory	0	0	50,000,000
Totals	1,149	25,467	$203,800,000

Table 5. Building damage outside of City of Los Angeles.

Does not include publicly owned structures. Data from various sources.

City	*Buildings damaged*	*Posted unsafe*	*Buildings demolished or to be demolished*			*Damaged chimneys*	*Estimated total dollar loss*
			Residential	*Commercial*	*Churches and schools*		
Alhambra	55	15	0	5	0	400	$2,000,000
Beverly Hills	135	0	0	2	0	1,000	800,000
Burbank	445	25	3	3	1	500	4,000,000
Compton	0	0	0	0	0	0	10,000
Glendale	*	31	13	23	5	3,250	2,000,000
Long Beach	*	0	0	0	0	0	*
Pasadena	10	4	0	0	1	2,000	2,500,000
San Gabriel	0	0	0	0	0	30	9,000
Santa Monica	20	1	0	0	0	30	50,000
South Pasadena	20	1	0	0	0	300	275,000
Vernon	30	5	0	0	0	0	100,000
Los Angeles County, including Newhall, Saugus, and Valencia areas	‡1,720	51	15	9	0	*	5,105,000
San Fernando City	*	270	95	†123	3	390	35,500,000
							$2,349,000 plus

* Not available.
† Posted "unsafe".
‡ May include cases of "chimney only" damage.

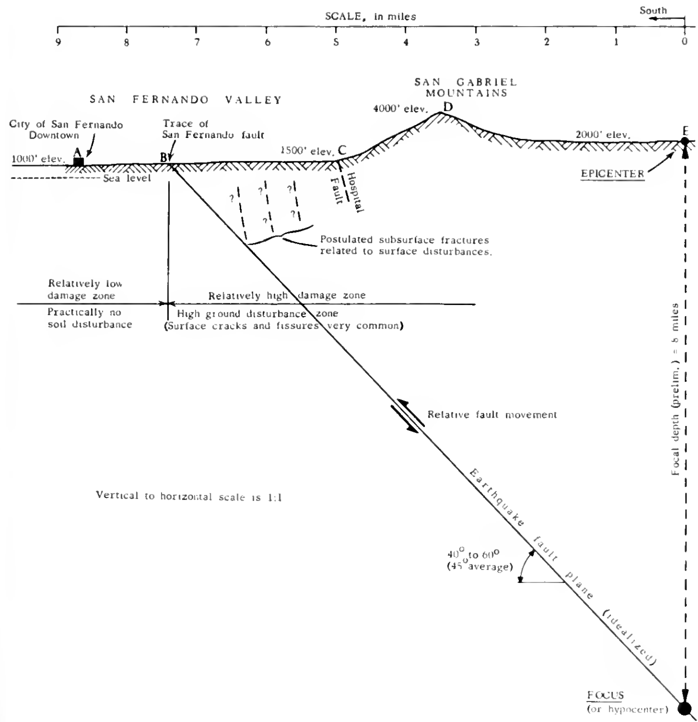


Figure 3. North-south cross-section through San Fernando Valley.

celerations of this earthquake were the highest ever recorded, being 104 percent of gravity (Maley and Cloud, 1971) for the greatest single pulse with a number of other peak accelerations being in the 50 percent to 75 percent of gravity range. Subsequently, Trifunac and Hudson (1971) have reported 125 percent of gravity peaks in two horizontal directions.

The *strongest* shaking began 1 to 2 seconds after the instrument started to record, and this *strongest* shaking lasted for about 8 seconds. The over-all strong motion lasted about 12 seconds.

The instrument was located on a rock outcrop at the left (south) abutment of the dam. The rock around the instrument was fractured by the earthquake, thus permanently tilting the instrument's foundation. The fracturing of the rock during the earthquake and the instrument's location on an outcrop may have significantly influenced the recording with respect to the unfractured rock—probably increasing it—although this cannot be proven. The 12-second duration of strong shaking is undoubtedly correct. It is interesting to note the Pacoima concrete-arch dam had no structural impairments, although the right (north) abutment was found to be slightly more than 1 inch higher than the other abutment after the earthquake.

The significance of this "highest-ever" recording may be debated for years to come. A true upper limit of horizontal acceleration of 75 percent of gravity on unfractured bedrock *for this earthquake* does not seem unreasonable to the authors instead of 104 percent or 125 percent as reported. (There undoubtedly is an upper limit for earthquakes, but such a limit is unknown.) This reduced value is reasonably consistent with the authors' observations of the highly intensified damage found along the nearby base of the San Gabriel Mountains: at Olive View Hospital, at the Veterans Administration Hospital, and in wood frame dwellings between them.

The full significance of the high horizontal earthquake accelerations and their resulting forces becomes more apparent when it is realized that modern codes require a lateral force coefficient of 13.3 percent of gravity for the conventional one-story rigid structures as compared to the possibly 75 percent of gravity actually observed. With factors of safety against major structural damage approaching twice the 13.3 percent value, or about 25 percent, it appears that the actual forces at Pacoima Dam could be interpreted as being three times as great as required by usual good practice as based on code requirements.

The reasoning, though incomplete, presented in the previous paragraph could readily explain, in part, the intensified damage found at Olive View Hospital, the Veterans Administration Hospital, and in wood frame dwellings located between them. However, extrapolation is not entirely satisfactory since the band of damage along the base of the San Gabriel Mountains containing these buildings was not a very wide band. The band of damage is particularly narrow for single-family wood frame dwellings. It has been observed in some other earthquakes that accentuated damage is found at the discontinuity between unconsolidated alluvial valley soils and firmer soils (or rock) in the foothills. The full significance of this band of accentuated damage requires much more study.

To summarize, the adequacy of present lateral-force code values for buildings, other than high-rise, may be insufficient by 100 to 200 percent, especially wherever there exists the potential for ground-disturbed areas such as those identified in the San Fernando earthquake. This condition may occur more frequently in metropolitan Los Angeles, particularly in its northern section, than previously believed. Considering this, the code cannot everywhere be offered as a reasonable "minimum" for safety.

Vertical accelerations. In addition to the larger-than-anticipated recorded horizontal accelerations and forces, substantial vertical forces were also exerted. Examples of the damage resulting from vertical accelerations are shown in the section discussing Olive View Hospital.

The authors observed "tossed earth", like freshly disc-harrowed land prepared for planting, on the top of the hills just north of Olive View Hospital. This suggested unusual vertical forces in addition to horizontal forces.

Similar evidences of vertical earthquake forces were found following the 1969 Santa Rosa earthquake, among others.

Presently, no American building code requires consideration of vertical earthquake forces in building design. Certainly, this void in the building codes must be rectified.

Soil Conditions

Earthquake motions are often substantially modified as they travel from bedrock through alluvial soil to a building. The structural characteristics of soils generally tend to be poor throughout the San Fernando Valley. Earthquake damage relating to the apparent amplification of seismic motions through soil is of major concern, particularly in some areas. Also, damage due to permanent differential settlements, lurching, and landslides is important. Such movements resulted in severe damage to the Jensen Filtration Plant and to the Juvenile Hall facilities in Sylmar.

Soil conditions at specific sites are discussed elsewhere in this paper. However, a general discussion, contributed by Herbert J. Recker, President of Pacific Soils Engineering, Inc., follows:

> The valley floor, encompassing some 160 square miles, is relatively flat with a gentle southeast gradient. Soil of the basin is alluvium derived from the parent bedrock of the boundary mountain system. The alluvium ranges in composition and consistency from very fine-grained, highly expansive clays in the southern part of the valley derived from marine shales (Modelo and Topanga Formations) of the Santa Monica Mountains to the very coarse-grained sand, gravel, cobble, and boulder sediments derived from the granitic rocks of the San Gabriel and Verdugo Mountains bounding the valley on the northeast. The alluvial deposits in the basin exceed a thousand feet in thickness and range from soft, wet, and highly compressible material, such as is found in areas to the northwest of the Sepulveda Flood Control Basin, to the relatively dense sand, gravel, and cobble deposits of the north-central valley area along the old Tujunga flood plain.

Types of Building Construction

Building sites for residential construction in the valley range drastically from building pads developed on natural grade or in shallow cut or fill throughout the main valley floor area to building pads created by deep cut and fill grading or over-the-slope construction in the hillside areas peripheral to the valley floor.

Building pads on natural grade or in shallow cut and fill typically use conventional shallow spread-type footings having nominal reinforcement except where expansive clay soils are present. Where it is determined that expansive clays (fine-grained soils which, when changed in moisture content, change in volume) are present in the foundation system, special treatment is required, such as: deepening of footings, use of additional reinforcement in both floor slabs and footings as well as use of granular base material, and moisture-barrier membranes beneath the house floor-slabs.

Where building pads are in deep cuts or are over-the-slope construction and pads may consist of engineered compacted fill which may reach a thickness of 100 feet or more, conventional shallow spread footings, nominally reinforced, have been used.

Construction sites for industrial and commercial (high-rise) buildings are primarily in the main valley area. Soil conditions governing the design of footing systems for these buildings are, as discussed above, quite variable, depending on the locality. As a general rule, one-story industrial and one- to three-story wood frame residential (apartment) structures may be satisfactorily supported on conventional spread footings with some sites requiring reprocessing (excavation and recompaction) of the upper few feet of surface soils in order to maintain footing settlements within tolerable limits. An alternative foundation treatment economically competitive with the reprocessing procedure is the use of drilled cast-in-place friction piles or caissons.

Faulting and Energy Release

The geological and seismological aspects of the earthquake are effectively treated by the authors of the companion papers in this volume. However, it is of value to re-examine briefly some of these aspects from an engineering viewpoint as it relates to earthquake-damage distribution.

Figure 3 is a cross section drawn looking west through the faulted region. The downtown district of the city of San Fernando is at the left and the epicenter at the right. Figure 3 is the authors' simplified and somewhat idealized interpretation of the available data.

With respect to figure 3, the earthquake's energy is stored as strain energy in the rock around the fault plane. Thus the earthquake's energy, which causes the vibrational damage, need not be (and usually is not) centered beneath the epicenter at the focus. The evi-

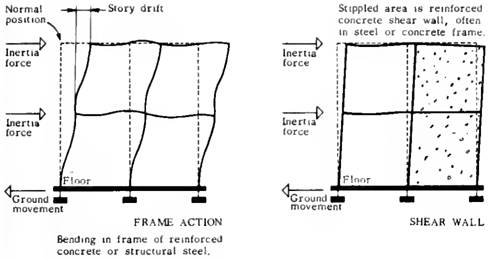


Figure 4. Diagram showing two methods of earthquake bracing.

dence available to date suggests that the centroid of the released energy volume was south of the epicenter and focus, possibly near a point between and beneath locations C and D in figure 3. Under these assumptions, the high concentration of damage between points B and C in figure 5 becomes more meaningful since the structures between these locations are much closer to the earthquake's energy center than implied by the attention given only to the epicentral distance.

The actual fault movement during the earthquake was complex and differed in many details from the thrust-fault idealization shown in figure 3. The movement also had a left lateral component.

The number of buildings astride the fault trace were few compared to the total number of buildings in the vicinity, but buildings on the fault trace usually are severely damaged. Moreover, building damage was more extensive than expected in areas north of the surface faulting when compared to similar buildings south of the surface faulting. One explanation of the greater damage north of the surface faulting is that the upward movement in this area resulted in severe vertical forces on structures. A witness at Olive View Hospital reported a sharp vertical upward movement as the first sensation.

Earthquake Bracing Systems

The amount of earthquake damage is not only a function of the building's strength, but to a great extent it is a function of the design methods used in achieving the required strength. A brief, simplified review of the principal bracing systems of the buildings discussed in this paper follows:

In a general sense, earthquake-bracing for all types of buildings usually may be divided into two types: frame action (by column and beam bending) and shear walls (by bracing walls). A combination of these may exist. Additionally, there are other variants, such as X-bracing systems, but these are comparatively few.

Frame action. In buildings where the steel or reinforced concrete frame resists earthquake forces, the columns and beams resist these forces in bending as may be seen in figure 4. The story-to-story movement, or story drift, may be as much as inches and still not overstress the columns and beams. However, story drifts, which normally are expected to occur in an earthquake, will shatter floor-to-floor partitions, continuous elevator-shaft and stair walls, stairs, plumbing, exterior walls, and other items extending between stories. Therefore, buildings with numerous partitions,

Figure 5. Map showing the distribution of damage with special reference to wood frame dwellings.

such as hospitals, hotels, and the like, can have substantial interior and exterior damage, possibly approaching 50 percent of building value, yet still be considered structurally safe. In recent years, increasing attention has been given to damage control of the building's outside skin features, particularly glass and precast concrete facings, but not to the interiors including stairs and elevators.

Shear walls. A shear-wall building (figure 4) is normally quite rigid when compared to a framed structure which resists earthquake forces by bending. In shear-wall buildings, the earthquake forces are resisted by the shear walls which act as bracing walls. Shear walls usually are of reinforced concrete but may be of reinforced grouted brick or reinforced hollow concrete block. The entire shear wall may rotate if the soil beneath its footings is relatively soft, causing localized damage around the wall. With low design-stress limits in shear walls, deflection due to shearing forces is negligible. Shear-wall construction is an excellent method of bracing buildings to limit their damage, and this type of construction normally is economically feasible up to at least 10 stories. However, the architectural and functional requirements must also be tailored to the concept of damage control and repair. Interior shear walls placed around elevator equipment cores and stairwells are comparatively difficult to repair and may interfere with function and occupancy during repair.

The one-story light industrial buildings in the San Fernando area are generally of the "box system" concept. Box system means that the roof and the exterior walls are intended to act in a manner similar to the top and sides of a box when the box is pushed sideways. The plywood roof deck (top of the box), therefore, would act as a horizontal diaphragm; that is, stressed skin. The exterior (and interior) unit masonry walls or tilt-up concrete walls parallel to the direction of ground motion act as bracing walls, or "shear walls". Interior columns do not resist any significant amount of earthquake force in the box system concept. This box system concept for earthquake resistive design is quite valid, and its effectiveness depends primarily on the connections between the structural elements. The size and number of openings in any shear wall are of major concern in the effectiveness of this system.

WOOD FRAME DWELLINGS

Survey of Dwelling Damage

The Pacific Fire Rating Bureau made a detailed study of the damage to over 12,000 dwellings throughout the most heavily hit area of San Fernando Valley. House-to-house inspection identified location; age; number of stories; floor construction; degree of damage to foundations, wood frame, interior finish by type of finish, exterior finish by type of finish (including veneer), and chimneys; ground disturbance, including faulting; and swimming pool damage, among others.

The hardest-hit regions of dwelling damage extended from upper Granada Hills north of Rinaldi Street on the west, across the valley to the east, and up into the San Gabriel foothills and Pacoima Canyon in Sylmar, figure 2. The eastern limits extended along the foothills into Pacoima, consistent with the damage around the Pacoima Memorial Lutheran Hospital. However, the entire survey is not depicted on figure 5. Although there was damage to older and poorly constructed dwellings beyond the southern survey limits shown on figure 5, the benefits from extending the detailed inspections southward were far outweighed by the meagerness of the potentially useful information.

Dwelling construction. Dwelling construction was almost universally of conventional wood frame. Exterior wall foundations were concrete and were continuous for the exterior stud walls of newer buildings. Soil throughout the inspected areas was generally weak alluvial sand and gravel.

Wood-frame dwelling construction in southern California has mostly followed two distinct patterns. One pattern is platform construction, which typically provides a continuous concrete foundation at the dwelling's perimeter. Interior supports for this system are square concrete piers, often embedded into the ground 6 inches, with posts and girders supporting the wood floor joist system above. A wooden sill bolted onto the top of the exterior concrete footing provides nailing for a crippled stud wall, used where the lot is not level. Otherwise, good practice would have the floor joist resting on the bolted sill, blocked continuously, and with diagonal or plywood floor sheathing providing the platform surface upon which the framing is erected.

A second type which prevailed more often was the concrete slab on grade (that is, on soil) with bolts embedded into the monolithic slab footing providing anchorage for a treated wood sill.

The wood framing described above typically followed the Los Angeles City Code Standard Type V sheet details. Bolted single sill plates, vertical studs 16 inches on center, and double top plates made up the structural wall system with a standard 1-inch let-in brace at each corner of the building and along every 25 lineal feet of wall.

Definitions of damage by construction component. The inspectors described damage to the various dwelling construction components in words. The following are, in very summary form, examples of the damage definitions which were used in the survey.

With respect to the wood frame, building distortions accompanied by a separation of the wood frame from its foundation or portions of the roof or walls distressed to a point of incipient failure defined the damage as *severe.* Minor cracking of the stucco finish along the line where dissimilar materials joined (such as along the wood sill join line) was assessed as *slight* damage when accompanied by minor cracking located diagonally at window corners. Damage appraised to qualify for neither slight nor severe then was designated *moderate*, a mid-range qualification.

Turning to another example, the degrees of damage to interior plaster and gypsum board were defined as follows: *Severe* when portions of the plaster were loose or had fallen as a result of extensive cracking of walls or ceiling or when the gypsum board (dry-wall) panels required replacement or retaping of joints; *slight* when old cracks enlarged and minor new cracks formed, with repair involving spackling of plaster or puttying of gypsum board panels; and *moderate* when damage was between the two extremes.

Similar definitions, also in much greater detail, were used for the other damage descriptions for construction components. Photos 2 through 8 show examples of damage.

Photo 2. Severely damaged one- and two-story wood frame dwelling on Almetz Street in Sylmar District.

Photo 3. The upper portion of this split-level wood frame dwelling on Almetz Street has collapsed into the garage.

Photo 4. Wood frame structure in center was two stories high; note automobile beneath.

Photo 5. Collapsed dwelling in course of construction on Tucker Street near Pacoima Dam.

Photo 6. Older wood frame dwelling in San Fernando.

Analysis of Dwelling Damage

The word description of damage to a construction component (that is, exterior finish, etc.) was converted to a percentage loss for the entire dwelling, and later a percentage loss was calculated for each statistical area outlined on the map (figure 5). Then, to assess the total dollar loss, a mean value of the dwellings within each statistical block was calculated.

The cost figures were broken down by construction component, by building value (less than \$20,000; \$20,000 to \$30,000; and over \$30,000), and by period of construction (pre-1940, 1940–1949, and 1949–present). All loss values exclude the value of the land. Repair costs were not increased by earthquake repair since there was a sufficiently skilled labor pool avail-

Photo 7. Older wood frame dwelling with unanchored stone veneer, in San Fernando.

Photo 8. Damaged reinforced brick chimney in heavily damaged new district near Pacoima Dam.

able and the demands on construction materials did not distort local markets—thereby providing loss data of good quality for this study.

The information from the dwelling damage survey and the cost data were computerized with the following results. Since the area selected for study was within the most heavily shaken area and the area of ground disturbance, the loss values are probably high.

Distribution of damage by construction component. Table 6 shows the percentage of the total number of the wood-frame dwellings as a function of the type of damage. There were more reports of "no damage" to exterior stucco (plaster) than to the interior plaster or gypsum board. It may be that the homeowner, who normally accompanied the inspector, was familiar with the interior cracks (new or pre-earthquake) whereas he may not have noticed exterior cracks. Also, repainting interior finishes often hides cracks which during an earthquake, may open and close slightly, destroying the paint bridge although the crack may not have lengthened. This "new" crack is, quite appropriately, new damage, even though paint within the crack may prove its pre-earthquake existence. Exteriors are less subject to this type of scrutiny.

Table 6. Percentage of the total number of wood frame dwellings as a function of type of damage.

Construction component	*Damage*			
	None	*Slight*	*Moderate*	*Severe*
Foundation	91.9%	5.8%	1.6%	0.7%
Damage to frame	78.8%	16.0%	3.3%	1.9%
Interior finish—plaster	4.2%	78.4%	11.1%	6.3%
Interior finish—gypsum board	12.1%	78.0%	6.5%	3.4%
Exterior finish—stucco (plaster)	20.7%	74.1%	4.0%	1.2%
*Brick chimney damage	67.6%	16.1%	6.6%	7.4%

* Total brick chimney damage was found in 2.3% of the cases. "Total" means exactly that, essentially no bricks were left standing, or the chimney was otherwise so damaged as to be non-repairable.

Of the interior finishes in table 6, "severe" and "moderate" damage occurred to plaster nearly twice as often as to gypsum board.

Brick chimneys (listed also in table 6), before reinforcing steel was used in their construction, were damaged in even slight shocks. Had chimneys not been generally reinforced, the "none" value would have been close to zero instead of 67.6 percent. While the present standards need continued improvement, they were impressive in reducing losses.

It is difficult to state the number of houses which were total losses. Certainly, when the damage exceeded 50 percent of the dwelling's replacement value, serious consideration should have been given to replacement. Serious damage to the frame is one excellent indicator; this study found 217 dwellings which had severe frame damage and probably were total losses to the owners. However, other interests often came in later to salvage and repair many of the newer buildings. Another guide to total losses was the number of houses condemned by the City authorities; these numbers, however, are based on inconsistent data and may reflect "instant redevelopment" by governmental authorities.

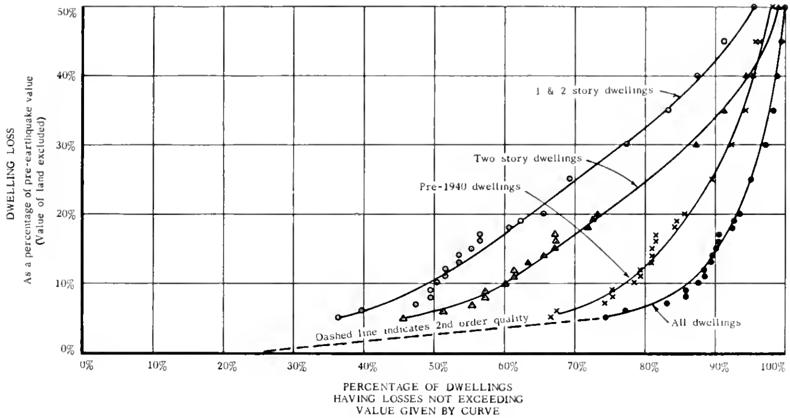


Figure 6. Percentage of loss of wood frame dwelling.

Masonry veneer, such as brick, was not common. A total of 75.7 percent of the dwellings had no veneer while 22.6 percent had no more than 1 to 10 percent of the exterior elevation veneered. Of those veneered, there was no damage or only slight damage to 94.5 percent of the structures.

Most of the 446 swimming pools inspected were along the foothills where much heavier-than-normal dwelling damage was found. Shifting sidewalks, cracking in street paving, and disturbed soil were common near or around the pools, all evidence of heavy ground shaking. Two hundred eleven pools had no damage; 137 had slight damage; 19 had moderate damage; and 79 had severe damage. The amount of damage was almost invariably related to the amount of ground disturbance around the pool.

The inspectors were asked to note all dwellings where sidewalks shifted or broke, underground utilities were out, or the soil was disturbed. These types of evidence were found in 10.1 percent of all dwellings inspected. It is reasonable to state that soil disturbance resulted in a significant increase in damage.

Percentage loss determinations. Figure 6 shows the results of the determination made for 12,037 inspected dwellings in the hardest hit areas contained in figure 5. The data in figure 6 do *not* include the many thousands of cases of negligible-to-very-slight damage —usually far less than 5 percent of value—found throughout much of eastern San Fernando Valley; nor does it include the extremely few cases of damage which exceeded 50 percent throughout this same area. In figure 6, the data for losses over 5 percent are of high quality but drop off quickly below 5 percent. Only the general case for losses of less than 5 percent has been plotted, and the data are of second-order quality.

Using "all dwellings" as a reference in figure 6, it is evident that older dwellings, such as those constructed before 1940 fared worse than did more recent construction. Two-story dwellings fared even more poorly; however, the sample was small (less than 3 percent of the total) and included many older buildings. Dwellings of part one and part two stories fared poorest of all; no doubt this reflected the particular design characteristics (photo 9). Interestingly, no essential difference could be detected in the relative performance of wood-joist floors vs. concrete-slab floors on grade, even though the structures with concrete-slab construction were usually newer.

Figure 6 leads to the following conclusions, provided the previously described qualifications are kept in mind:

1. About 25 percent of all of the dwellings in the hardest-hit area had losses over 5 percent. This represents 1 percent of all of the dwellings in the San Fernando Valley considered in this study; stated in a different way, about 3,200 dwelling

Photo 9. Left section of this dwelling was originally two stories (over garage) and attached to one-story section on right. Garage areas normally have comparatively little bracing.

units out of more than 300,000 had 5 percent or greater loss.

2. There was no noticeable difference between the performance of concrete-slab floors and wood-joist floors.

3. One-story dwellings performed substantially better than did two-story dwellings, and much better than combination one-and-two-story dwellings.

4. Modern dwellings performed noticeably better than did older dwellings.

Geographic distribution of heaviest dwelling damage. The 12,037 dwellings examined were divided into 62 tracts. The boundaries of each tract were determined on the basis of area, number of dwellings, and distribution of damage, in order to minimize differences. The area shown in figure 5 includes about 80 percent of these tracts.

In the preparation of figure 5, the average percentage dollar loss per dwelling was computed and rounded off to the nearest whole percent; these loss percentages are shown for each tract. The calculated average loss per dwelling is 6.6 percent for all tracts.

The heavily stippled tracts in figure 5 include all those having the average 6 percent loss or greater. At least two zones of higher-than-average dwelling damage exist: one contiguous with the zone of faulting in the San Fernando Valley and the other along the base of the San Gabriel Mountains. Additionally, the accentuated damage along the base of the San Gabriel Mountains includes Olive View Hospital and the Veterans Administration Hospital which are discussed elsewhere in this paper. Figure 5 is somewhat misleading since the zone of intensified damage was normally no more than several city blocks wide.

In another and independent approach, we plotted all structures inspected and posted "unsafe" by the City of Los Angeles as shown by the dots on figure 5. (Unsafe structures within the city of San Fernando were not plotted as the bases of comparison were not compatible.) The dots on figure 5 (unsafe structures) included structures that were not dwellings. The "unsafe" posting did not indicate the amount of loss and may have been influenced by non-structural considerations. However, the correlation between the Los Angeles posted "unsafe" structures and the dwelling-damage pattern is excellent. It will be noted that the heaviest concentration of unsafe structures was against the base of the hills (shown at the top of the map) and along the fault breakage.

The reason for this intensified damage appears to be related to the discontinuity between the soft alluvial soil in the valley and the much firmer soil and rock in the foothills. Certainly, it is a geologically hazardous area and, surprisingly, more hazardous on a tract basis than the tracts showing fault movement.

Mobile Homes

While mobile homes are structurally quite different from wood-frame dwellings, their earthquake-performance characteristics are similar. A mobile home is a coach unit which is transported on wheels to a site where it can be raised off its wheels and leveled. The wheels, but not the axle spindles and drum unit which the wheels and tires fasten to, may be removed and stored.

To set up, the coach is rolled into place above one of several types of piers placed at intervals of about 6 feet along the main frame. A jack on the top of each pier is then screwed into contact with the undercarriage until the coach is level and steady on the mounts. Where there are soft soils, concrete-block masonry or flat cement patio blocks are used to spread the load so as to prevent settling. Utilities are then hooked up; an aluminum skirt is attached around the base; and stairs are placed at the doorway.

The trailers that were significantly damaged did not have the piers anchored to the ground, nor were the screwjack levelers at the top of the piers fastened to the frame of the coach. The support was structurally poor; the earthquake vividly demonstrated this. The precast-concrete pyramid-shaped piers rolled over, dropping the coach and often piercing the plywood floor. Photo 10 is an example of typical damage.

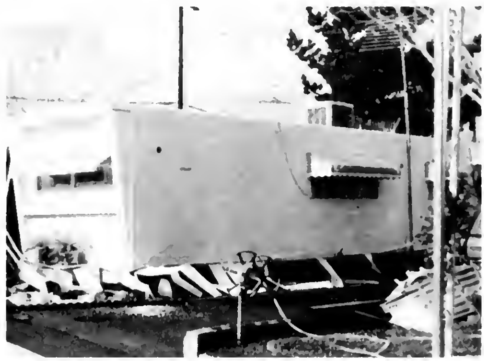


Photo 10. Mobile home shifted off its foundations; note damage to skirt. *Drew P. Lawrence photo.*

LIGHT INDUSTRIAL CONSTRUCTION

This examination of the performance of light industrial construction included 61 buildings, all in the hardest-hit area of the San Fernando Valley. Probably all examined structures were built within the past 10 years, and therefore all should have been designed and constructed in accordance with the earthquake-bracing provisions of the building codes of the City or County of Los Angeles. The Los Angeles earthquake provisions and the structural requirements for construction types discussed herein, generally speaking, are essentially the same as those found throughout California. Fifty-six of the buildings were examined in detail in this study; they represent, by far, the best earthquake test of their construction type to date—an experience of substantial value for all earthquake-prone areas.

The buildings were one story and one floor but two stories high, and few had mezzanines. All were in two industrial tracts (Arroyo tract and Bradley tract).

Their locations are shown on figure 2. These structures were all light industrial buildings with plywood roofs and tilt-up concrete or unit-masonry walls, except for a small section of one plywood roof which was of undamaged poured gypsum. For all practical purposes, all buildings examined had plywood roofs.

Of the 61 buildings in the two tracts, 56 were examined in detail, both inside and out; interior access to the other five structures was denied. The data gathered included detailed measurements, assessment, and photography of the damaged areas; the examination of construction drawings when available; and the review of actual repair costs when available. Damage was catalogued for each structure—stating the type and extent of roof damage, ground-floor damage, wall damage, and the degree of soil disturbance at the site. Dollar losses were computed as well as the pre-earthquake "present worth" values determined.

Construction Characteristics and Earthquake Design Features

All unit-masonry walls (brick and hollow concrete block) were reinforced with steel and had roof-to-wall ties as required by the building code. Some had floor-to-wall ties. All reinforced concrete walls were of the tilt-up type (precast reinforced concrete wall panels which were tilted into place), with the tilt-up wall panels usually interconnected by poured-in-place pilasters of reinforced concrete. In a few structures, structural steel columns were used instead of reinforced concrete pilasters, but no significant difference in damage pattern was noted.

Whatever the wall material, all buildings had plywood roofs which were intended to act as diaphragms ("stressed skin" in one sense of the phrase) in the event of an earthquake. The diaphragms typically were supported by wood joists and beams which were supported in turn on wooden glulam or tapered steel beams. (Glulam beams are normally fabricated from glued-together 2″x4″ or 2″x6″ wood.) Interior columns, where present, were usually steel, although some structures had concrete and wood columns.

Typical roof diaphragm-to-wall connection detail consisted of a 4-inch-thick ledger which was bolted to the wall. Purlins were hung from the ledger in metal hangers and a plywood diaphragm nailed to the ledger and purlins.

Soil in both tracts was structurally weak alluvium. However, nominally sized reinforced-concrete spread footings and/or drilled-concrete friction piling are quite adequate for all normal conditions. Soil in the Arroyo tract was described in a soils engineering report for a specific site: ". . . . . The boring penetrated 5½ feet of dense cohesionless sand containing 30 to 50 percent of gravel and cobbles to 12 inches in diameter. Drilling was very difficult because of caving and the large proportion of cobbles. Only one relatively undisturbed sample could be obtained from this formation. . . . ."

Types of Damage—Arroyo Tract

The Arroyo industrial tract is on the north edge of the San Fernando Valley adjacent to the foothills of the San Gabriel Mountains (figure 2). Significant ground breakage, including faulting, in and about some of the buildings caused extensive damage. Severe damage to other buildings was principally due to vibration.

While buildings on sites where there was significant ground breakage were often badly damaged, the degree of damage resulting from soil disturbance was not necessarily in keeping with outward appearance of the building. The obvious damage to the building shown in photo 11 would, at first glance, indicate possible total loss to the structure. The badly damaged portion of the building is an entry walkway of wood frame construction. The main portion of the building, though damaged, performed reasonably well; the corner at the edge of the compression zone in the soil was only slightly affected.

Photo 11. Arroyo light industrial tract. Damage to steps due to ground movement. *E. G. Zacher photo.*

Conversely, in another case, the outward appearance of the building did not indicate how severely it was damaged. The earth movements at this location caused one structure and an adjoining one to move together so that the first building is now from 8 to 12 inches *inside* the formerly adjacent structure (photo 12). This movement, when combined with a reported 6-inch separation between buildings prior to the earthquake, indicates ground shortening and/or building movement of 24 inches or more; this is corroborated by the amount of overriding of the sidewalk in front of the building (photo 13). The resulting damage to the two structures can be seen in photo 14.

Unfortunately, the type of damage directly or indirectly due to ground displacements cannot be overcome by existing earthquake-resistive design-and-construction practices, nor is it practical to do so. However, site-planning can and must avoid geologically hazardous locations as far as the state of the art allows.

The remaining structures in the Arroyo tract were not known to have been subjected to severe ground displacement. The only reinforced-concrete tilt-up-wall building in this tract to have a wall panel collapse was not on a site having visible *major* ground displacement, although the building lengthened about 6 inches in a north-south direction. The severe damage that was

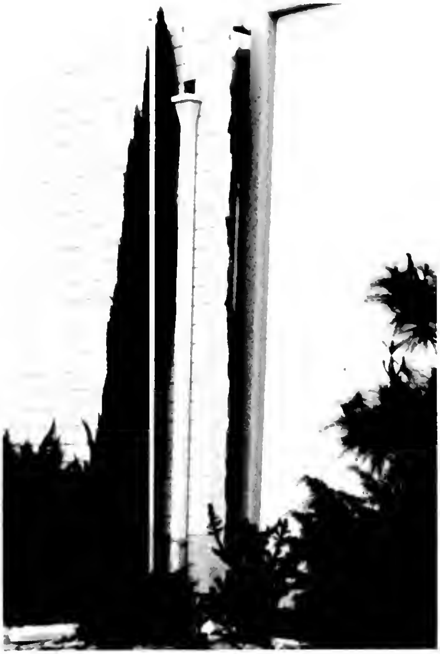


Photo 12. Arroyo light industrial tract. One building is now from 8 to 12 inches *inside* of the other due to ground movements. *E. G. Zacher photo.*

Photo 13. About 27 inches of sidewalk overriding in front of one of the buildings shown in photo 12 indicates the local extent of ground surface shortening. *E. G. Zacher photo.*

Photo 14. Damage due to ground surface shortening in the Arroyo light industrial tract. *E. G. Zacher photo.*

sustained by this structure, photo 15, must be attributed partially to questionable construction details for both tilt-up-wall and diaphragm connections (photo 16) as well as to the increase in building length.

Types of Damage—Bradley Tract

The Bradley tract is approximately 3 miles west and slightly north of the Arroyo tract. Ground disturbance in this tract was markedly less than that in the Arroyo tract. As a result, the damage to the buildings in the Bradley tract must be attributed more to

Photo 15. Tilt-up wall panel failed, bringing down portions of the roof and mezzanine floor. Arroyo light industrial tract. See also photo 16. *John Meehan photo.*

Photo 16. This is a detail of photo 15. Drilled expansion bolts from floor slab (shown) to tilt-up walls failed to hold panel in place. Similar failures occurred where the 3-inch dowels from the tilt-up wall to the pilaster proved to be completely inadequate. *E. G. Zacher photo.*

the vibrational ground motions and less to differential ground displacements.

More than half of the buildings in the Bradley tract had portions of their roofs collapse; see, for an example, photo 17. Only three buildings had partial wall collapse; see, for an example, photo 18. A large number of buildings sustained damage at the roof-beam (or girder)-to-wall connections. These connection failures were noted where portions of roofs collapsed (photo 19) or where collapse did not occur but was incipient. The partially collapsed roofs which exerted lateral

Photo 17. Collapsed roof, Bradley light industrial tract.

Photo 18. One of three structures in the Bradley light industrial tract that had one or more sections of its walls fail.

Photo 19. Top of concrete pilaster in tilt-up wall where glulam beam had been anchored. Also note that plywood has pulled away from wooden ledger which was bolted to the tilt-up wall. *E. G. Zacher photo.*

pressures on the freestanding walls, as well as those sections of the roof which completely collapsed, indicated a reserve of strength at the foundation level and an inadequacy of the generally accepted roof-to-wall standard connection details. While the tilt-up walls rarely collapsed, there were many small cracks in them. Separations or movements at the precast wall-to-poured-pilaster juncture were very common, with or without wall collapse.

Typical damage to buildings with dock-height floors was cracking of wall panels, and in some cases, cracking of columns on the first floor level. This type of damage occurred even if the roof diaphragm remained intact.

The observed damage to all structures is summarized in table 7.

Table 7. Summary of observed damage to light industrial buildings.

Damage: Element and degree	*Wall construction*		*All buildings*
	Tilt-up	*Unit masonry*	
Concrete floor slab:			
None, or hairline cracks (to one-eighth inch)	15	11	26
Moderate cracking (to one inch)	13	7	20
Severe cracking (over one inch)	7	3	10
Walls (includes five buildings for which access denied):			
None, or slight damage	11	9	20
Moderate damage to some portions	12	6	18
Severe damage to some portions	14	4	18
Collapse of some portions	2	3	5
Roofs:			
None, or slight damage	11	13	24
Moderate damage to some portions	5	3	8
Collapse of some portions	20	4	24

Data Analysis

The 56 buildings in the Arroyo and Bradley tracts which were examined in detail gave the opportunity to determine dollar losses accurately and establish pre-earthquake present-worth values. In summary, the pre-earthquake "present-worth" value was $11,699,000 while earthquake loss was established at $2,065,000, or 17.7 percent.

The other industrial tracts located *outside* the heavily shaken area had far less damage, usually negligible or none, except along the Soledad road north of the area under study. It is reasonable to believe now that the average loss for buildings throughout the San Fernando Valley was less than 3 percent, possibly less than 1 percent.

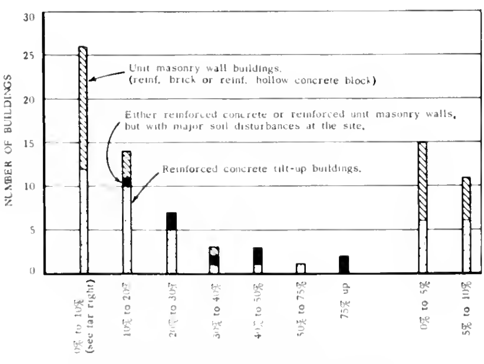


Figure 7. Loss distribution by wall type for light industrial construction.

Figure 7 shows the loss distribution by type of wall construction. Clearly, almost half of the buildings examined had less than 10 percent loss; the right side of figure 7 shows losses under 5 percent to be common.

Figure 7 also shows that unit-masonry (reinforced brick and reinforced hollow concrete block) performed well. The data in figure 7 should not be interpreted to mean that unit-masonry walls performed better than tilt-up walls, despite the rapid comparative drop-off in loss to unit masonry. The sample is too small and other problems, such as the larger diaphragm areas in tilt-ups, do not allow accurate quantitative comparison between the relative performance of brick and hollow-concrete-block walls with tilt-ups. However, based on field observations, their performances appeared to be about equal. In any event, the data show that unit-masonry and tilt-up walls can be equally effective earthquake-bracing elements, but there is no available information to compare them with poured-in-place reinforced concrete walls.

Further examination of figure 7 indicates major ground disturbance at the site increases the loss, and this is more vividly pointed out in greater detail in table 8. Clearly, when there was no or slight ground disturbance at the site, losses were under 20 percent.

Table 8. Effect of soil disturbance on building damage

Ground disturbance site	*Dollar loss to present worth (pre-EQ), per building*						
	0 to 10%	*10 to 20%*	*20 to 30%*	*30 to 40%*	*40 to 50%*	*50 to 75%*	*Over 75%*
	Tabulated values are number of buildings						
None or slight	12	3	--	--	--	--	--
Noticeable	13	7	3	1	--	--	--
Moderate	1	3	2	1	1	1	--
Major	--	1	2	1	2	--	2

Ground disturbance indicators:
None or slight: No cracks or hairline cracks to one-eighth inch in paving or ground.
Noticeable: Cracks in paving or soil to seven-eighths inch.
Moderate: Cracks in paving or soil to 1½ inches. Offset in curbs, buckling of sidewalks or curbs, indicating 1- to 2-inch compressional effects.
Major: Cracks over 1½ inches. Compressional effects in paving, paving, sidewalks, and curbs, indicating differential movements of more than 2 inches. Faulting.

A 30 percent probable maximum loss in value for all equivalent earthquakes would cover virtually all structures, except those on sites having such significant ground disturbances as faulting, landslides, and structurally poor ground.

Buildings subjected to ground upheaval and lateral thrust such as that found in the Arroyo tract cannot be expected to come through such an experience unscathed. Much of the damage found, however, could have been avoided or markedly reduced had careful attention been given to the design and construction details. The need for adequate and appropriate geologic and soil information is very important. While the need is obvious, the scientific state-of-the-art of soils engineering and the identification of geologic hazards leaves much to be desired at this time.

All evidence indicates that the buildings in these two industrial tracts were subjected to seismic forces greater than the design forces required in any American building code. Despite this evidence, no building collapsed totally nor did any appear to be on the verge of total collapse.

Based on reviews of the plans or physical inspection, or both, there were buildings where the horizontal reinforcement shown on the drawings or provided would not comply with the minimum requirements of the Uniform Building Code. Unquestionably, had these buildings been appropriately designed for code forces, they would have survived markedly better.

Present practices for roof-to-wall ties are quite inadequate. They probably represent the most critical detail in terms of hazards. Had a more positive anchorage system of purlin-to-hanger and then to-wall been required, far less damage would have resulted. The ends of all main framing roof members such as glulam girders should be anchored to the walls (or pilasters) in a manner that will take twice the total seismic design force due to the contributing tributary area. When these members are spliced, the splices should provide continuity to transmit these lateral forces across the building. The secondary framing perpendicular to the main framing should be treated similarly except that the wall connections and splices might be concentrated on members not more than 8 feet apart.

The failure of the typical wood diaphragm-to-wall connection was so widespread and similar that it indicates a basic weakness in this system. Furthermore, the type of failure here results in a sudden, or "brittle", type of collapse which can be hazardous. Connections must be developed which have adequate redundancy or toughness so that sudden collapse is prevented even though large overstress occurs. Dynamic tests should be conducted on full-scale assemblies to determine the mode of failures and to make necessary improvements.

The joining of precast-concrete tilt-up-panel walls must be improved. The prevailing practice, as noted from plans and from physical inspections, of extending only half of the horizontal wall reinforcement into the poured-in-place concrete pilaster and also providing less than the minimum length of bar lap necessary for full-bar development, is inadequate. Full-bar development (by bond) is mandatory for improved performance.

HIGH-RISE CONSTRUCTION

Prior to the 1933 Long Beach, California, earthquake, buildings in the metropolitan Los Angeles area, including high-rise construction, were not generally designed to resist earthquake forces. Until 1956, a Los Angeles City Ordinance limited the height of buildings to 13 stories or 150 feet, at which time a revision in the ordinance removed this height limit for steel-framed structures. Shortly thereafter, concrete and any other system of materials was authorized for high-rise construction when certain tests and studies were performed. This change in the height limit was more likely due to economic pressures and civic pride than to advances in the technology of earthquake engineering.

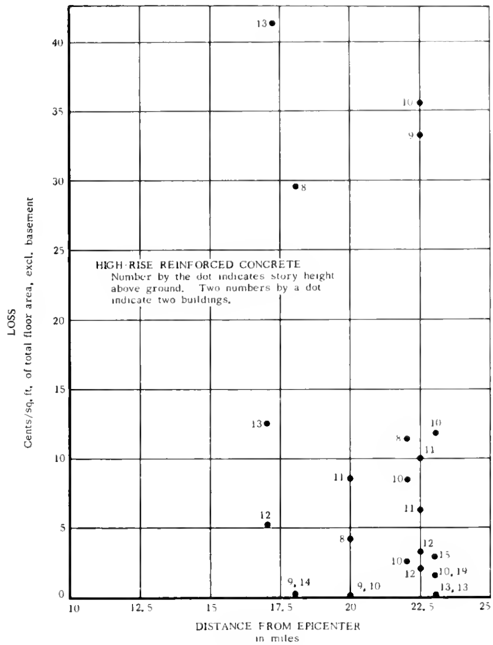


Figure 8. Losses to earthquake resistive high-rise reinforced concrete buildings.

Over 190 buildings, eight stories and higher, have been built in Los Angeles County since 1947, and all have been designed to be earthquake-resistive. In addition, there were probably over 100 older high-rise buildings throughout the same area built before 1933 and therefore not specifically designed to resist earthquake forces.

Modern Earthquake-Resistive Buildings

Figure 8 is a compilation of reported losses to 29 reinforced concrete buildings, 7 to 20 stories in height, located from 13 to 24 miles south of the instrumentally determined epicenter of the earthquake (see figure 9). The city of San Fernando and the Sylmar and Pacoima districts of Los Angeles are approximately 5 to 7 miles south of the epicenter, and one may thereby reduce by that amount each of the distances in the table when considering a building's proximity to the severely shaken area or to the center of energy-release of the shock.

Figure 10 is a compilation of reported losses to 30 completed steel-frame buildings, 6 to 42 stories in height, all in the general vicinity of the concrete structures (figure 9).

A pair of 52-story steel-frame buildings being constructed in downtown Los Angeles were struc-

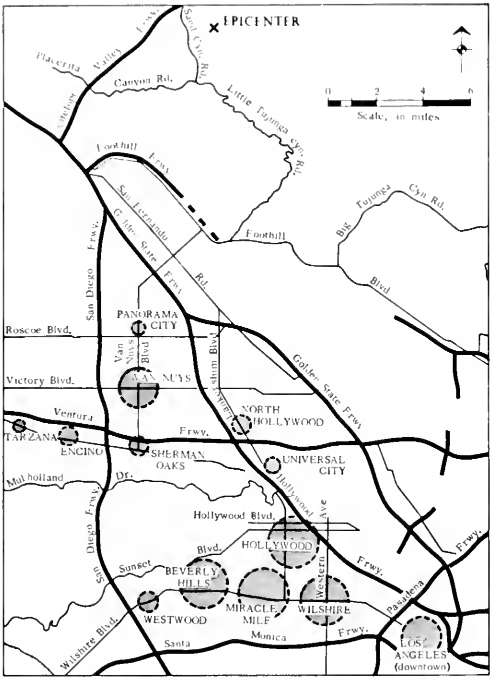


Figure 9. Districts containing high-rise construction and their geographic relationships to the epicenter.

turally damaged with a reported loss of $400,000. However, the authors know of no significant structural damage to completed steel-frame high-rise buildings although several reinforced-concrete buildings were structurally damaged. With those exceptions, observed damage patterns were about the same.

Flexibly framed buildings, whether concrete or steel, received mostly cosmetic damage on February 9 when relatively stiff stair-elevator and utility cores within the frame experienced large story-to-story relative movements. In taller buildings elevator cables and the containment of elevator counterweights were damaged and caused further damage. These features must receive more design attention in the future.

The high percentage of damage to store windows and other damage along Ventura Boulevard suggest an amplified ground motion for the valley alluvium where it terminates at the Santa Monica Mountains along the southern boundary of the San Fernando Valley. This higher-than-average damage may be a reduced-scale counterpart to that observed along the north edge of the valley in the vicinity of Olive View Hospital and the Veterans Administration Hospital.

Figures 8 and 10 show losses in terms of cents per square foot of total floor area (above ground) as functions of epicentral distance and of types of construction (concrete and steel). Losses include building and equipment repair costs. Occasionally, loss of contents was included when it could not be segregated, but these losses were small and have no significant effect on the conclusions.

The following conclusions may be drawn from an examination of figures 8 and 10:

1. Steel-frame and reinforced-concrete high-rise generally performed equally well if they were 15 to 25 miles from the epicenter, with exceptions as noted below.

2. Where there were exceptions, they were usually adverse with respect to reinforced-concrete construction, as follows:

Dollar loss in cents per square foot	*Material*
680.	Concrete *
192.	Concrete *
65.5	Concrete *
41.7	Concrete
35.5	Concrete
35.0	Steel
33.3	Concrete
29.5	Concrete
28.3	Steel
28.0	Steel

* Beyond the limits of figure 8.

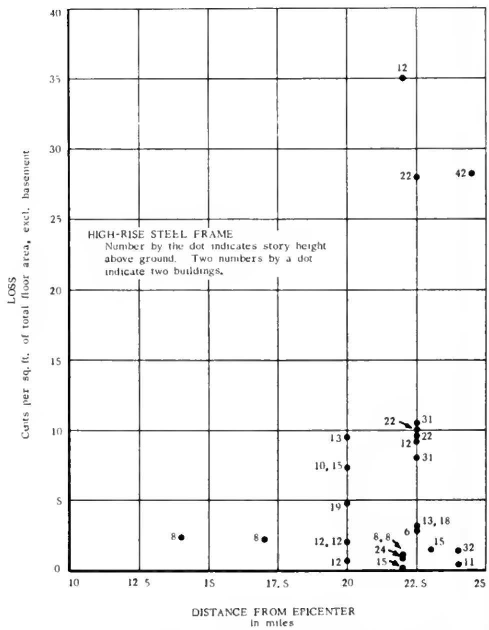


Figure 10. Losses to earthquake resistive high-rise steel frame buildings.

Non-Earthquake-Resistive Buildings

Older non-earthquake-resistive high-rise buildings performed quite badly when compared to modern high-rise construction, based on limited selected information on older structures in the downtown Los Angeles area.

The eight buildings examined were erected between 1906 and 1916, prior to enactment of earthquake requirements in the Los Angeles City code; that is, the engineering design considered only the vertical loadings and not earthquake forces. However, during that construction period, fireproofing of the *steel frames* often was a monolithic concrete covering which inherently developed a strong "composite" structure of steel and concrete. This is not common under present construction methods which employ a sprayed-on light-weight asbestos material.

Six of the buildings examined had steel frames, and the other two had reinforced-concrete frames. Dollar loss as a percentage of assessed market value ranged from 5 percent to 26 percent. These losses, when compared to the less than 1 percent loss for almost all modern earthquake-resistive buildings, make a substantial case for best modern practice in high-rise construction in *moderate* earthquakes.

HOSPITALS

Four major hospital complexes in the San Fernando Valley contained buildings which were structurally damaged; two of them had buildings collapse. The U.S. Office of Emergency Preparedness reported that 17 hospitals were damaged or destroyed—one Federal, one County, and 15 private hospitals. The collapsed and structurally damaged buildings were at Olive View Hospital, Holy Cross Hospital, Pacoima Memorial Lutheran Hospital, and the U.S. Veterans Administration Hospital. They are shown on figure 2. Other hospitals in San Fernando Valley were damaged, but none required closure.

Many of the privately owned medical-center buildings distributed throughout the San Fernando Valley sustained varying degrees of damage. At least three of them were significantly damaged; namely, Indian Hills Medical Center, Foothill Medical Building, and Pacoima Lutheran Professional Building.

Nursing homes were also damaged. Most interesting among these is the Foothill Nursing Home where surface faulting traversed the site (photo 20), lifting the structure about 3 feet above the street in front of it. This one-story reinforced hollow-concrete-block structure was unoccupied and unused at the time of the earthquake. Although racked by vibration and permanent ground displacements beneath it, the building did not collapse. Its earthquake performance under these conditions was comparatively excellent—certainly the life-safety hazard was substantially less than that at some buildings at the Olive View and Veterans Administration Hospitals.

All of the foregoing specifically mentioned buildings were in the area of ground disturbance or very close to it. Not unexpectedly, their earthquake damage represents the heaviest found to buildings used for these purposes.

Photo 20. Foothill Nursing Home on Foothill Boulevard, Los Angeles. Sidewalk has been raised 3 feet by faulting with respect to the street. *The Ledger (La Cañada Valley) photo.*

The case history of Olive View Hospital and a summary description of the Veterans Administration Hospital are included in the following paragraphs because of their special importance.

Olive View Hospital

The licensed 880-bed Olive View Hospital, owned by the County of Los Angeles, consists of a large number of buildings, 35 of which may be 50 or more years old and many of which were constructed prior to the introduction of earthquake-resistive construction that followed the 1933 Long Beach shock.

The complex of buildings which forms Olive View Hospital is shown on figure 2. All of these structures are in the band of substantially heavier-than-normal damage; see, for example, figure 5 which shows the distribution of damaged dwellings near the hospital complex.

Not all buildings were seriously damaged, although heavy damage was common. Several recently constructed one-story concrete-frame structures located about 100 yards west of the new hospital were undamaged. Damaged structures included masonry as well as wood-frame construction. However, of surprise and great concern was the damage to a newly completed group of three buildings. Figure 11 is a plot-plan of these three buildings and photo 21 is an over-all view.

Three people died at this hospital, all in the newly completed earthquake-resistive Medical Treatment and Care Building. That any lives should be lost in, and excessive damage occur to, a structure that was believed to be earthquake-resistive is disturbing.

Medical Treatment and Care Building. The Medical Treatment and Care Building, henceforth called the Medical Building, has five stories and a basement. Since it is on a gently sloping site, the basement is above grade on the east and south elevations, below grade on the north elevation, and mixed above and below grade on the west elevation. The basement retaining walls were self-supporting and structurally

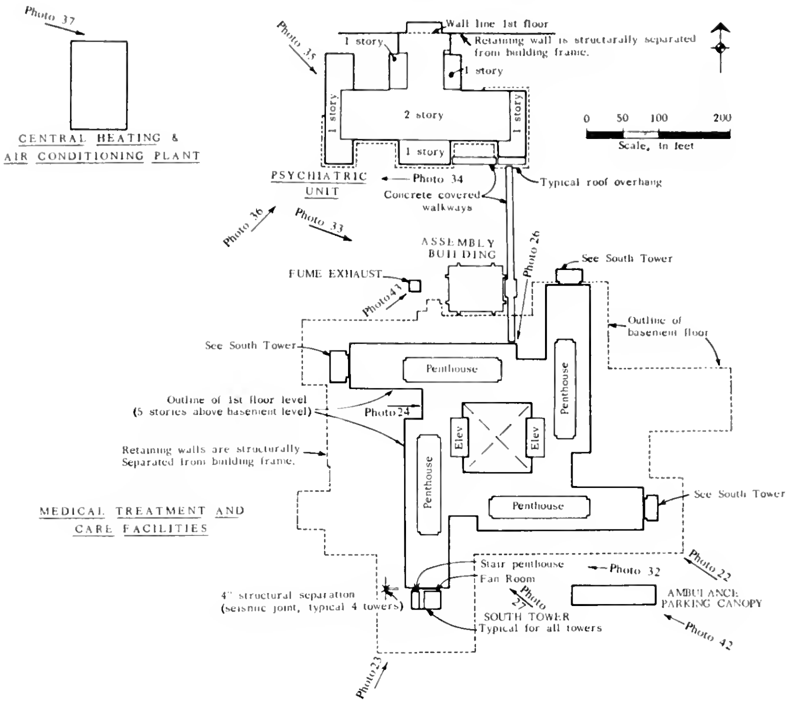


Figure 11. Plot plan of new additions to Olive View Hospital.

Photo 21. Olive View Hospital. Central Heating and Air Conditioning Building, lower right; Medical Treatment and Care Facilities; center, Psychiatric Unit, center left.

separated from the building frame by 4 inches. As shown in figure 11, the basement extends well beyond the confines of the outer walls of the rest of the building, except at the north stair-tower. Generally, landscaping existed above the basement where it extended beyond the building's exterior walls.

The Medical Building was of reinforced-concrete construction, completed in 1970. Foundations were reinforced-concrete spread-type on alluvial soil. From a structural standpoint, one may view the Medical Building as five distinct buildings, with the four towers containing the stairs and day-room-areas structurally separated 4 inches from the main building. All stair-towers except the one on the north were supported on the first-floor framing over the basement area. The north stair-tower had its own foundations outside the basement.

Test borings and excavations made before construction started showed brownish gray fine sand, medium gravel, and boulders at least 3 feet in diameter.

A total of 606 patients was in this structure at the time of the shock, plus 98 staff members. Bed capacity was 820.

Medical Treatment and Care Building—earthquake-bracing system. The earthquake-bracing consisted of both frame bending and shear walls. With respect to the main section of the building (that is, excluding the stair towers), the first story and basement-level earthquake-bracing was in the form of column bending. Concrete walls around the elevators and interior stairs in the first story were, by designer's intent, constructed with a slip-joint which went through these walls and thereby prevented them from acting as shear walls. As a result, the first-story bracing had aspects of the flexible first-story concept which has been known for years but rarely used. Above the first story, shear walls were used for the bracing system.

The four stair towers next to the main building were, as noted before, structurally independent of the main building.

Medical Treatment and Care Building—earthquake damage. Earthquake damage was excessive in the first story and basement, with little damage above the first story. This abrupt change in rigidity at the second-floor level undoubtedly contributed to the severe damage at the first-story level. The building was leaning as much as 2 feet in a northerly direction after the shock, with essentially all of this permanent offset (story drift) in the first story. The first story nearly collapsed.

Photos 21 through 34 show views of the exterior elevations and some of the detailed damage. The spirally wrapped reinforced-concrete columns (photo 24) performed much better than the tied columns (photo 25). Certainly there was a substantial reserve of strength in the spirally wrapped columns, or the building would have collapsed, as it was so far out of plumb. Some steel reinforcing bars in columns were broken; where the bars were fractured, the fractures were near, but not in, the welds (photo 26). Precast-concrete wall panels failed when portions of the building collapsed (photo 27). While nonstructural precast-concrete facings should not be expected to be intact after the building begins to collapse, it is not unreasonable to hope for shattered panels which do not leave their backing walls.

Photo 22. Medical Treatment Building, toward the southeast corner. Note overturned stair tower at right, broken columns, and collapsed ground story under landscaping. *Los Angeles County Fire Department photo.*

Photo 23. Medical Treatment Building, looking at southwest corner. South stair tower overturned and collapsed on one-story portion; roof of stair tower is center right. *Los Angeles City Fire Department photo.*

There was evidence of pounding of the first floor against the retaining walls. Damage in the first story was probably increased by the frame suddenly striking the retaining walls when the building oscillated northward. This may be one of the reasons for the 2-foot building offset to the north.

Damage to first-story ceiling tile (photo 28), elevator doors (photo 29), telephone equipment in the basement (photo 30), and other features was excessive.

Photo 24. Spirally wrapped reinforced concrete column; compare with tied column (photo 25). Note distorted mullions for glass and about 2-foot offset in first story.

Photo 26. Some vertical reinforcing steel in tied columns broke, usually near the weld splicing bars as shown here.

Photo 25. Tied reinforced concrete column having little remaining strength. Ties broke, and the vertical steel broke as shown in photo 26.

Photo 27. Precast concrete wall panel on ground fell from supporting structure at emergency entrance (basement level).

At least some columns in the basement areas apparently failed due principally to excessive *vertical* forces. Photo 31 shows basement-column failure on the south elevation; there was no significant evidence of horizontal forces sufficient to cause this damage. Photo 32 shows the failure of an interior basement-column below landscaping. These, and many other basement-column failures, strongly indicated an excessively high level of vertical earthquake forces.

The four stair towers were of reinforced-concrete construction. Three towers which were supported by tied reinforced-concrete columns overturned, while one on its own footing leaned to the north (photo 33). It is important to note that the failures were due

Photo 28. Fallen ceiling tile, first story of Medical Treatment Building. Glass was originally vertical.

Photo 31. Shear failure of reinforced concrete column in ground story.

Photo 29. Inspectors at jammed elevator doors, first story of Medical Treatment Building.

Photo 32. Column punched through the roof slab supporting a landscaped area at the first floor level.

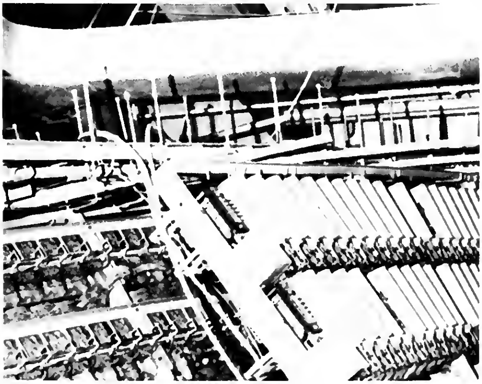


Photo 30. Telephone equipment damage, basement of Medical Treatment Building. *John Meehan photo.*

Photo 33. Note partially overturned stair tower at left. Fume Exhaust Building in center right had broken cantilevers (photo 43).

to overturning and not to shear. The failure of three towers and partial failure of one tower, all containing stairs intended for evacuation, made them unusable after the shock.

Photo 34, shows four overturned concrete benches, each of which is too heavy for a person to turn over. The concrete-covered walkway in the background leaned as shown after the shock.

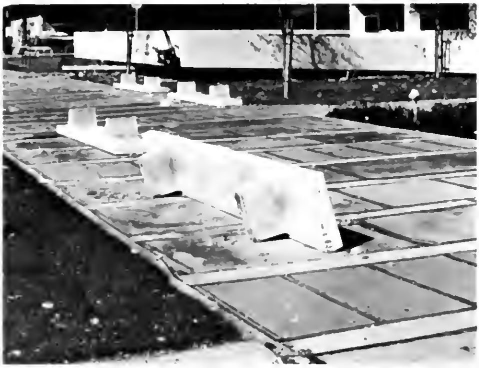


Photo 34. Overturned concrete benches north of the Medical Treatment Building.

Medical Treatment and Care Buildings—general comments. Power failed; communications were out; four stair towers were useless; elevators were inoperative; and the hospital was on the verge of collapse. The staff did not panic, and patients were successfully evacuated to other hospitals. Three lives were lost; two when power failed and the electrically operated life-support systems stopped and the third when a person who attempted to leave the building was struck outside by a collapsing portion of the building. The time of day (6:01 a.m.) found very few people in the first story, basement, and stair towers. Life loss would have been significantly higher had the earthquake occurred later in the day.

No faulting was found in the area, but the ground motion was sufficiently severe to crack pavements and, in some nearby places, leave cracks in the soil.

Duration of the strong motion was short, probably not much different from the 12 seconds recorded at the nearby Pacoima Dam. Continued shaking would have progressively weakened the columns and undoubtedly caused building collapse.

The building cost $25 million and probably represents a total loss, although some suggestions have been made for saving the upper stories.

Psychiatric Building. This structure was a two-story reinforced concrete-frame building designed in 1965–66 and constructed between 1966 and 1969. The plan was roughly T-shaped, with a first floor area of about 40,000 square feet and a second floor area of about 23,000 square feet.

The roof and the second floor were reinforced-concrete pan-joist systems with 4½-inch slabs and 12-inch-deep joists except for 8-inch-thick two-way slabs in the center east-west bay of the second floor. The first floor was a 4-inch-thick reinforced-concrete slab on grade. Walls were mostly glass except for several non-bearing, reinforced hollow concrete-block filler wall panels in both the first and second stories. The hollow concrete-block wall panels were separated 1 inch from structural frame at their sides and top. Lightweight concrete was specified for all concrete above grade.

The lateral-force-resisting system consisted of reinforced concrete roof and second floor diaphragms which distributed lateral forces to the rigid frame bents along both axes. Second-floor and low-roof diaphragms were at two levels, with the low roof being about 2 feet below the second floor. This complex layout resulted in numerous different rigid frames in both directions.

Very small torsional loads were produced because of small eccentricities between centers of rigidity and mass at both levels.

An approximate evaluation of the lateral-force adequacy indicated that the ultimate capacity of the columns in shear and bending would be reached with loads produced by accelerations between 15 and 25 percent of gravity.

Cause of the collapse was ground motion, both vertical and horizontal, which induced stresses in the lateral-force-resisting elements beyond their ultimate capacity. Specifically, the first-story columns failed, dropping the second floor onto the first floor (photo 35). The second floor also was translated toward the south and east, rotating slightly counter-clockwise when viewed from above. The center of rotation was somewhere near the northeast corner. Photo 36 shows the remains of a reinforced-concrete column.

A possible cause for the building rotation could be the performance of the north-south reinforced-masonry non-bearing walls in the southeast corner area. These non-bearing walls probably acted as shear walls during the excessive deflections which led to failure and thereby prevented the east portion of the

Photo 35. Psychiatric Unit, of which the first story collapsed. *Los Angeles County Fire Department photo.*

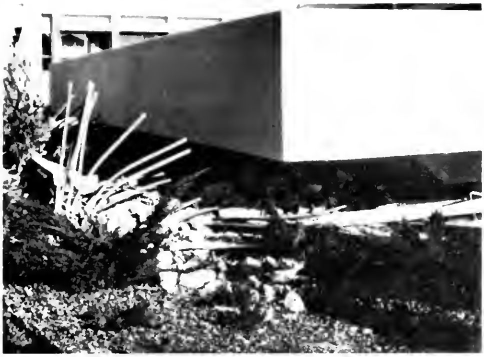


Photo 36. Psychiatric Unit, with first story roof now on the ground. Dowels (reinforcing steel from footing) show that building moved laterally during failure.

building from translating as far south as the west portion.

The second story columns were severely cracked and bent but did not collapse. Interior partitions, ceilings, fixtures and other contents at the second story level were also seriously damaged.

It is reasoned that column failure started with shear-type failures which combined with strong vertical loading, causing the concrete to crack and shatter.

The time of day proved to be most fortunate. According to the hospital authorities, normal day use would have found about 300 persons in the collapsed first story. Undoubtedly, a very large majority of these persons would have been killed had the earthquake occurred during working hours.

Central Heating and Air Conditioning Plant. The Central Heating and Air Conditioning Plant is a one-story-and-mezzanine independent building (figure 11). By contrast, it performed well as a building, although the equipment did not. This mixed-construction building showed some damage to reinforced hollow-concrete-block shear walls but lost its steel flat-bar x-bracing in a temporary wall (photo 37). The original value of the building has been placed at $1.5 million, with building loss estimated at 20 percent to 25 percent.

Boilers shifted as much as 4 feet and caused a small fire. Photos 38 and 39 show the damage to piping and other equipment. Possibly the most important lesson, however, comes from the failure of unanchored and poorly anchored equipment required for standby power. Photo 40 shows the failure of unanchored batteries required for activating this standby power, and photo 41 shows the damage to the emergency generator. It is mandatory that standby power equipment, as well as emergency communications equipment, be strongly and very conservatively braced. Bracing of this type of equipment is too often neglected by all concerned.

Other structures. In the immediate vicinity of the three previously described buildings are several other new structures. Photo 42 shows the seriously damaged ambulance carport south of the Medical Building; there was evidence of high vertical acceleration. The Assembly Building was also badly damaged and leaning to the north. Photo 43 shows the typical serious cracking of the roof cantilevers of the Fume Exhaust Building north of the Medical Building, again explainable by high vertical acceleration.

Much older construction elsewhere on this hospital site also was heavily damaged. Photo 44 shows the collapse of an unreinforced hollow-concrete-block building. Old wood-frame structures typically fell when their unbraced cripple-studs gave way (photo 45); this type of damage very rarely leads to loss of life.

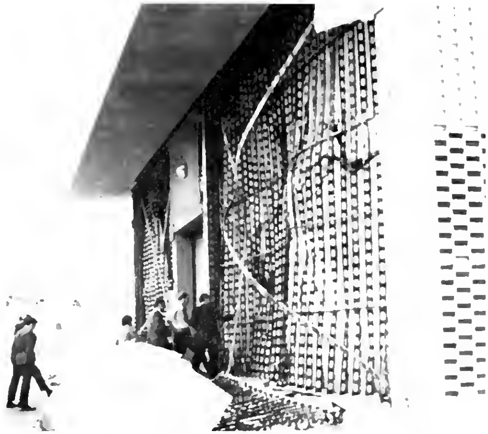


Photo 37. Rear of Central Heating and Air Conditioning Building.

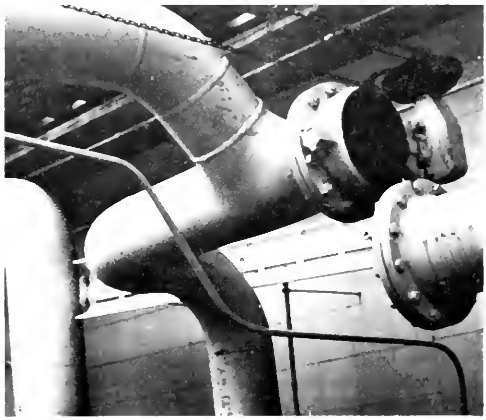


Photo 38. Broken piping, Central Heating and Air Conditioning Building.

Photo 39. Equipment damage, Central Heating and Air Conditioning Building. *John Meehan photo.*

Photo 40. Fallen unanchored batteries required for activating standby power operation.

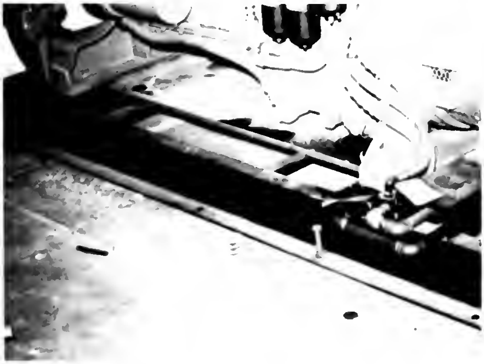


Photo 41. Emergency generator off its mountings and inoperative.

Photo 42. Carport collapsed on several ambulances.

Photo 43. Cracked cantilever beam at Fume Exhaust Building. This structure may also be seen in photo 33.

Photo 44. Collapsed unreinforced hollow concrete block building at Olive View Hospital.

General comments. There apparently was no faulting at the hospital site but much evidence of heavy shaking leading to ground disturbance. Soil on

Photo 45. Damage to old wood frame structures at Olive View Hospital.

the hill near the tank was shattered by the shaking; the pavement around the building was buckled or cracked; and cracks were opened in the ground.

The foregoing are consistent with very heavy horizontal ground shaking on soft soil. This is partially confirmed by the several overturned concrete benches (photo 34); roughly made calculations suggest earthquake forces of two-thirds (67%) of gravity. This is well over code-required forces; this subject is more thoroughly discussed in the section on earthquake forces. Vertical acceleration was also excessively high as evidenced by failed cantilever beams and by some broken basement columns.

It may be stated in summary:

1. Vertical and horizontal earthquake forces substantially exceeded the code values. Certainly the building codes need strengthening in this regard for structures located in similar types of geologically hazardous earthquake settings. Also, the basic philosophy of what constitutes acceptable damage, considering the actual lateral-force levels, must be re-examined.
2. The damage to the recently completed reinforced-concrete structures appears to be excessive when compared to other construction types at the site. The need for greater ductility and toughness was emphasized by the superior behavior of spirally wrapped reinforced-concrete columns as compared to tied reinforced concrete columns.
3. Structures having facilities vitally needed after an earthquake, such as hospitals, must contain special damage-control features necessary for continued safe occupancy. Damage control must be included in the mechanical and electrical features, as well as in the structure.
4. Only the time of day prevented a loss of life in terms of hundreds of persons instead of only three.

Veterans Administration Hospital

The complex of buildings which constitutes the Veterans Administration Hospital is located at the base of the San Gabriel Mountains adjacent to Pacoima Canyon (figure 2). Pacoima Dam, with its high recorded earthquake forces, is little more than a mile away.

Construction details are still not adequately known to the authors. However, much of the pre-1933 construction is of reinforced concrete, including the collapsed structure.

Photo 46. Air view of Veterans Administration Hospital. ***Los Angeles Times photo.***

The San Fernando Veterans Administration Hospital (420 beds) consisted of about 26 buildings and their additions built before 1933 and therefore without earthquake-resistive features. Earthquake-resistive features were incorporated into the design of about 21 buildings and their additions built after 1933.

The older buildings were generally constructed with reinforced-concrete frames which were designed to carry only vertical loads; unreinforced hollow-clay-tile exterior filler walls were used in conjunction with these frames. A few were constructed with wood frames and unreinforced hollow-clay-tile bearing walls.

The newer major structures generally had reinforced-concrete frames and/or bearing walls.

Photo 47. Partially collapsed building having hollow clay tile filler walls, Veterans Administration Hospital. *Los Angeles County Fire Department photo.*

Photo 48. Rescue operations, Veterans Administration Hospital. *Los Angeles City Fire Department photo.*

Permanent ground movements probably did not play a significant role in the damage at this site; rather, severe ground-shaking was the principal cause of the damage. Four of the old (pre-1933) buildings totally collapsed during the initial movements of the main shock while the remainder suffered varying degrees of damage, mostly severe. Four of the newer buildings suffered some damage, but the remainder of the earthquake-resistive buildings were essentially undamaged.

This is a good example of the superior performance of structures especially designed to resist strong earthquake forces when compared to the older buildings without earthquake-resistive features.

Forty-seven persons died in the collapse of the structures or later from injuries suffered in the collapse, and this represented the majority of the deaths in the entire earthquake. Some damage details and rescue operations may be seen in photos 47 and 48.

It should be clearly noted that the Veterans Administration Hospital is located in the band of accentuated damage found along the base of the San Gabriel Mountains.

Hospital Damage: A Special Problem

The exceptionally heavy damage to hospital buildings, nursing homes, and medical-center buildings points out a very serious public problem. Hospitals and related occupancies are a much greater and more vital need after a disaster than before it. However, the minimum earthquake requirements of virtually all building codes allow all occupancies, *including hospitals*, to receive structural damage, providing the people within the structure can safely leave the building. More specifically, the "Recommended Lateral Force Requirements and Commentary" (1968) by the Structural Engineers Association of California states on page 33 regarding expected building damage:

1. Resist minor earthquakes without damage.
2. Resist moderate earthquakes without structural damage but with some non-structural damage.
3. Resist major earthquakes, of the intensity of severity of the strongest experienced in California, without collapse, but with some structural as well as non-structural damage.

Seismologically and geologically speaking, the San Fernando earthquake was a moderate shock, but the damage to hospitals exceeded even that expected for a major earthquake. The future does not look good if Olive View Hospital is an indicator.

The aforementioned criteria *may* be satisfactory for office buildings, but surely public interest is much better served if hospital structures are designed with sufficient damage-control features so as to assure that the structure will remain functional after the event. This means placing severe limits, not only on permissible structural damage, but on permissible elevator damage, telephone and other communication damage, standby-power damage, and the like. Certainly, hospitals must be kept out of fault zones. Any attempt to replace these facilities should come under the scrutiny of all disciplines, with site location based on more factors than being politically favorable.

GEOGRAPHIC DISTRIBUTION OF DAMAGE

Building damage was, of course, very heavy along the surface expression of the fault. However, the geographic distribution of damage on either side of the fault ruptures is of principal interest in the following discussions.

The distribution of heaviest dwelling damage in San Fernando Valley is clearly evident in figure 5. These data are of particular significance because of the large number of dwellings examined, the use of consistent sampling methods, and the reasonable uniformity of dwelling contruction. It will be noted in figure 5 that a band of intensified damage exists along the base of the San Gabriel Mountains as well as along the surface faulting.

Equally impressive to the authors, but requiring a more subjective evaluation, was the geographic distribution of damage to certain hospitals, certain medical buildings, the Sylmar Juvenile Hall Facility, the Jensen Water Treatment Plant, and two groups of freeway overpasses—all substantially north of the surface faulting. The locations of these structures roughly formed a band of damage on thick, coarse aluvial soil overlying thousands of feet of partly consolidated, sharply downfolded sedimentary materials parallel to the base of the foothills of the San Gabriel Mountains (figure 12 , and Oakeshott, 1958, plate 3, Geologic Structure Sections). This is also true for the area between the surface faulting and the band of damage at the base of the San Gabriel Mountains. However, by any standard known to the authors, the over-all damage north of the surface faulting was substantially greater than south of it. It was evident that the locations of accentuated damage to the structures mentioned in this paragraph were in close agreement with the dwelling damage pattern in figure 5.

Another viewpoint on the geographic distribution of damage was obtained from a review of damage to the underground water, sewer, and gas systems. Figure 12 lists the breaks to these systems (excluding service breaks) in accordance with the tract numbers established for the dwelling study. These data are from incomplete maps and other partial records since repairs were not completed when the information was gathered, particularly for the city of San Fernando. Additionally, within that city some lines were so badly shattered that they were abandoned and it was not reasonable to count the breaks. However, within the city of San Fernando, faulting was definitely the cause of the large majority of the breaks.

It is evident that the underground lines suffered most heavily in the same tracts where dwelling and other structures were most heavily damaged. Excluding fault-related breaks to water mains, gas mains, and sewers, the remaining breaks can be primarily attributed to violent shaking beyond the alluvium's capacity to remain intact. The foregoing is based on numerous pipe breaks examined by the authors during field investigations. The locations of the pipe breaks strongly suggest that the surface of the thick alluvial materials folded downward in a syncline along the base of the San Gabriel Mountains was the most heavily shaken if it can be assumed that the structural strength and dynamic characteristics of the alluvial materials were not vastly different throughout the studied portion of the area shown in figure 12. Based on information available to date, this assumption seems reasonable.

Exact correlation between the number of pipe breaks and building damage is not to be expected because, as mentioned, pipe-breakage data are incomplete. Additionally, the number of miles of mains in each tract was not compiled at the time of this writing. (Obviously, the number of breaks per mile per tract would be more meaningful than the total number of breaks.) Lastly, the pre-earthquake condition of the lines is not known to the authors, although we do know of some breaks in lines that were so badly rusted that only moderate pressure-surges within the lines could have caused failures. Despite these inconsistencies, the evidence strongly indicates that damage to the underground water, gas, and sewage mains correlated well with building damage.

While the locations of pipeline damage and building damage were in good agreement, observable *permanent* ground differential displacements outside of the faulted areas were not so clearly related and were few in number. Asphalt pavement cracks were common, and shifted concrete sidewalks (and sidewalk cracking) were common. However, in the case of cracks in asphalt pavement, the width of the pavement crack was substantially greater than the width of the ground crack (if any) below the pavement crack; photo 49 is one such example. This suggests that the violent ground motions left more visible evidences in the asphalt pavements which were more rigid, and probably much stronger, than their supporting soils. It appears that the underground-pipeline failures followed a pattern similar to the asphalt-paving breakage. Photos 50 and 51 are examples of pipeline damage which is closely related to fault movement in these instances.

Photo 49. Asphalt paving cracks were almost invariably much wider than the soil cracks.

The geographic distribution of damage in this section of the San Fernando Valley clearly points out areas requiring detailed instrumental and theoretical investigations. Similar geologic conditions appear to be very common throughout the Los Angeles Basin as well as throughout California. The identification of

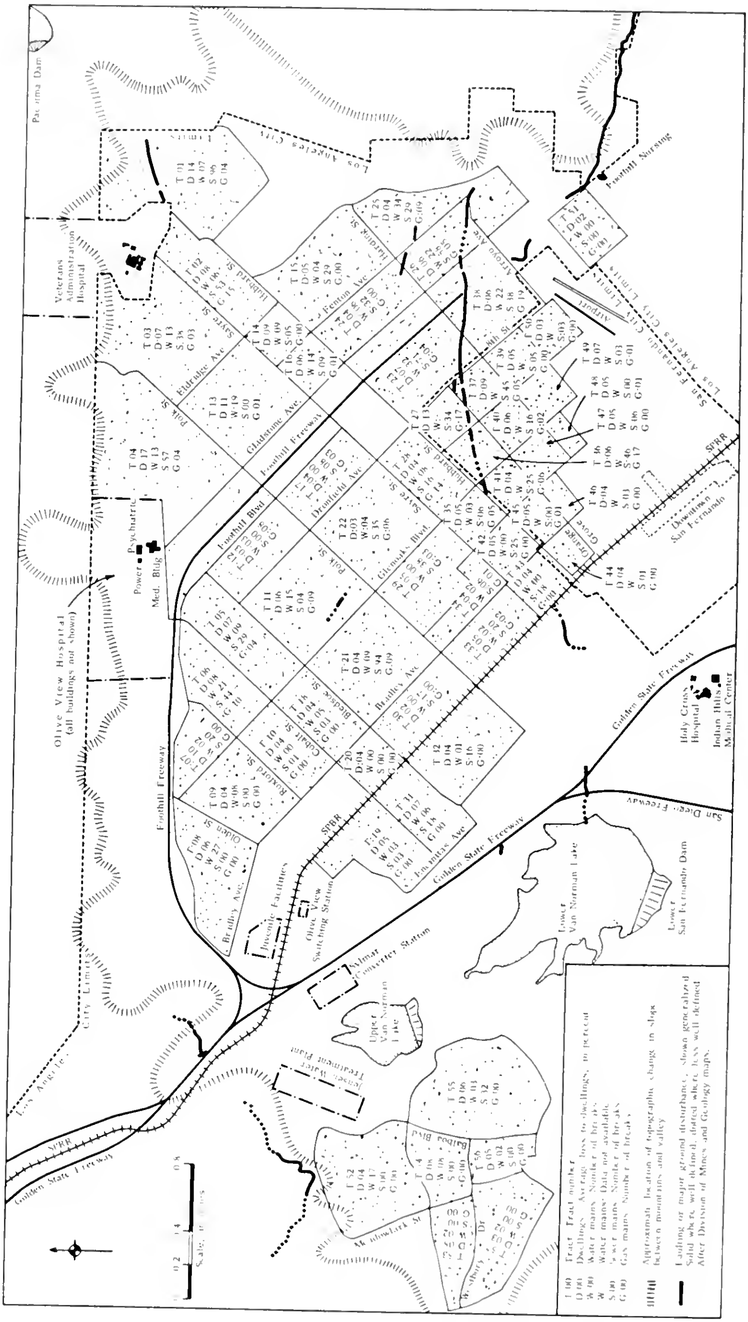


Figure 12. Distribution of damage to dwellings and to water, gas, and sewer mains.

Photo 50. Typical view of water pipe joint separations and shears near joints.

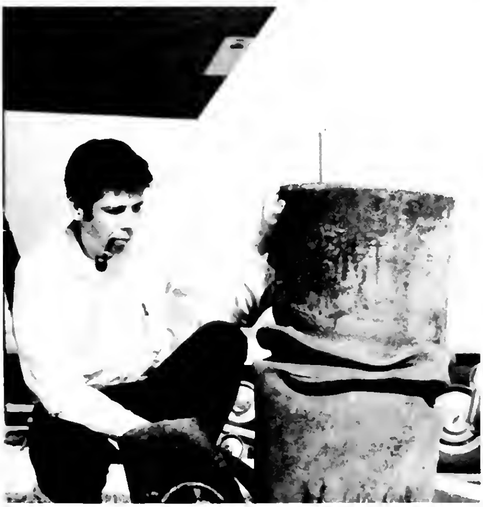


Photo 51. Compressive forces buckled 16" steel gas pipe in Glenoaks Boulevard, San Fernando. *Southern California Gas Co. photo.*

these areas is mandatory for progress in good land-use planning in seismic areas as well as providing the basis for building-code provisions necessary to minimize damage. Intensified damage on alluvium has been mentioned in reports on other earthquakes. For one example, Miller (in Steinbrugge, 1970) points this out as one possible explanation for intensified damage in the 1969 Santa Rosa, California, earthquakes.

It is a feeling on the part of some engineers that an apparently related problem exists in the band of intensified damage found along (or near) Ventura Boulevard. The damage along this southern edge of San Fernando Valley (figure 2) strongly suggests that motion here may have also been amplified. Because of Ventura Boulevard's greater distance from the earthquake's energy source, the damage patterns were not nearly as pronounced as those found to the north. It seems reasonable that the previously recommended studies should include both the north and south boundaries of the San Fernando Valley.

In conclusion, detailed instrumental and theoretical studies of the dynamic properties of soil, particularly the alluvial material and Tertiary-Quaternary sedimentary formations, leading to land-use planning regulations and building code revisions, if necessary, must be given high research priority.

ACKNOWLEDGMENTS

No study such as this one could succeed without the unselfish support of many persons.

The authors are grateful to Mr. Harold S. Morr, General Manager of the Insurance Services Office, for having made available the resources of his organization and their compiled data.

Helpful engineering advice and comments were received from many sources. Mr. John F. Meehan (Office of Architecture and Construction, State of California) provided field support, photographs, and factual information. Mr. Henry J. Degenkolb (H. J. Degenkolb and Associates), Mr. Edwin G. Zacher (H. J. Brunnier Associates), and Mr. Herbert J. Recker (Pacific Soils Engineering, Inc.) reviewed or provided manuscript material in critical sections of this study. Mr. Robert A. Olson (formerly with the U. S. Office of Emergency Preparedness) frequently assisted with advice and background information.

Mr. Edward C. Brinley, Jr. (The Hartford Insurance Group), Mr. Drew P. Lawrence (Industrial Indemnity Company), and Mr. Frank Rindone (State Farm Fire and Casualty Co.) assisted in providing access to information.

Acknowledgment is made of the valuable assistance rendered by officials of public utilities, Los Angeles County, the numerous cities, and other agencies in the gathering of pertinent information relative to earthquake effect upon public services.

The Carnegie Institution of Washington, through their H. O. Wood Fund, gave financial support necessary for the preparation of this paper.

CHAPTER 26

Performance of Public School Buildings[1]

by J. F. Meehan[2]

The San Fernando earthquake of February 9, 1971, clearly demonstrated the vast difference in the performance of public school buildings constructed under the provisions of the Field Act and school buildings constructed before its enactment. School buildings constructed since the enactment of the Field Act in 1933 were damaged far less than those built before that year. Practically every conceivable form of school building construction was exposed to the San Fernando earthquake motion. No public school building collapsed.

A strong-motion instrument on the east abutment of Pacoima Dam recorded the earthquake accelerations that were the highest ever recorded anywhere in the world—in the 0.50 to 0.75-g range with several high-frequency excursions to 1.25 g. The duration of the strong motion portion was approximately 12 seconds.

LEGAL CONSIDERATIONS

The Field Act was enacted by the California State Legislature within about one month after the March 10, 1933, earthquake in Long Beach. That 6.3 Richter-magnitude earthquake, with its epicenter just offshore from Newport Beach, extensively damaged structures throughout the Long Beach, Compton, and Whittier areas, as well as causing some damage to downtown Los Angeles buildings. School buildings within this area were heavily damaged, and many collapsed. Although there may have been more, it is reported that one student died as a result of injuries sustained from falling debris in a Norwalk High School gymnasium (oral communication from K. V. Marr). The Long Beach earthquake occurred at 5:54 p.m. on a Friday afternoon. Had the 1933 Long Beach earthquake occurred during school hours or at a time when the buildings were occupied for school functions, the death toll would have been horrifying. If the 1971 San Fernando earthquake had occurred during such occupied hours, it is very doubtful whether any deaths would have occurred in any public school buildings constructed since the enactment of the Field Act.

The Field Act applies only to public school buildings through all grades, up to and including junior or community college level, constructed in 1933 or later; it does not apply to private schools.

The Act, found in Sections 15451 through 15465 of the California Education Code, requires the Department of General Services to approve or reject the plans and supervise the construction of all new school buildings regardless of cost and additions and alterations to school buildings if the cost of such work exceeds $10,000. Plans must be prepared by an architect or structural engineer, and the construction must be under his charge.

The Act requires continuous construction inspection by an approved inspector. It also requires all those in charge of construction (the architect, structural engineer and other professional engineers, the inspector, and the contractor) to provide a verified statement indicating that the construction conforms to the approved plans and specifications in every particular. The Act states that anyone who makes a false statement in the verified report or violates any of the provisions of the Act is guilty of a felony. The Act also requires the Department of General Services, if requested, to examine existing school buildings and report on their structural condition. It establishes fees for the services performed by the State, requires the Department to adopt regulations, and makes other related provisions.

The Schoolhouse Section of the Office of Architecture and Construction in the Department of General Services provides the services required of the State by the Field Act.

All public school plans are prepared by architects or structural engineers in the private sector, and the general construction supervisor is the responsible charge of such architects or structural engineers. The plans and construction are reviewed by structural engineers in the State Schoolhouse Section. The plan review is rather detailed, whereas the construction review is rather broad, as the field representatives in the Schoolhouse Section have many projects simultaneously under construction. This field review is, in general, an extension of the plan review; further, the field engineer provides many other services to the school board.

The Field Act does not contain building regulations, but it does require the California State Department of General Services to adopt detailed building

[1] Submitted for publication July 5, 1972. A more complete report will be given in the EERI/NOAA report on this earthquake, which will be distributed by the U.S. Department of Commerce.

[2] Research Director and Supervising Structural Engineer, Schoolhouse Section, California Office of Architecture and Construction.

regulations. These regulations are published in Title 24 California Administrative Code. Title 24, CAC, contains basic building regulations which are at this time basically the 1970 Uniform Building Code and are applicable to all State buildings. It also contains exceptions to the basic regulations for special occupancies such as for public school buildings. Title 21, California Administrative Code, contains the same special building regulations given in Title 24, CAC, applicable to public school buildings, further, it contains testing and inspection requirements for schools and the operational regulations adopted to enforce the provisions of the Field Act.

The Field Act does not apply to those public school buildings constructed prior to 1933. Recent legislation revised the Garrison Act, Section 15503 through 15518, California Education Code, to require that all public school buildings built before 1933 have their structural condition determined by January 1, 1970. If found unsafe, the buildings cannot be used for school purposes after June 30, 1975, unless they have been rehabilitated to meet the requirements of the Field Act. The law absolves the school board members of personal liability, if prescribed steps are taken to alleviate the hazards.

PUBLIC SCHOOL BUILDING DAMAGE

At the time of the San Fernando earthquake, there were 110 masonry buildings in use by the Los Angeles Unified School District which had been constructed prior to the enactment of the Field Act and which had not yet been strengthened to meet those standards. All pre-Field Act buildings in this district had been previously examined, and the worst had been replaced or strengthened over the years. This last group had been considered to be the best of the lot and were scheduled for strengthening in the future.

In addition to the 110 masonry buildings, there were 53 wood-frame buildings, 409 portable buildings, and 3 bleachers built prior to the Field Act which were in use. After the San Fernando earthquake, all of these pre-Field-Act buildings were re-examined by a special committee of leading earthquake engineering experts who recommended that some buildings be demolished immediately because of their damage or inherently hazardous construction, that some buildings be rehabilitated for continued use, and that some buildings be abandoned before June 30, 1975. Within 1½ years after the San Fernando earthquake, the Los Angeles Unified School District had removed from service or rehabilitated about 100 of their pre-Field-Act school buildings.

Shortly after the earthquake, all school buildings in the Los Angeles Unified School District were examined. At that time, there were over 660 schools, consisting of over 9200 individual buildings. The examination included both pre-Field-Act buildings and post-Field-Act buildings. This examination clearly showed the relatively high performance of the post-Field-Act buildings. Major structural failures and construction defects were noted in the pre-Field-Act buildings, whereas what defects there were in most post-Field-Act buildings were minor.

The most common type of damage found in post-Field-Act buildings was in finish materials. Plaster was cracked, without structural significance, merely requiring patching and repainting; ceiling construction was damaged, and parts of ceiling materials fell to the floor; light fixtures were damaged or fell to the floor; mechanical items such as heaters, air conditioner units, duct work, and heater grilles were displaced; and equipment on shelves was thrown to the floor. A few structural defects were observed.

***Table 1.** General breakdown of cost estimate for minor repairs to buildings and sites in the Los Angeles Unified School District.*

Approximate number of schools	*Building and site repair cost estimate*
160	None
390	Under $1,000
80	$1,000 to $5,000
20	5,000 to 20,000
10	20,000 to 50,000
6	50,000 to 100,000
3	Over 100,000

Information in table 2 indicates the amount of actual or estimated dollar loss to all public school districts surrounding the area affected by the earthquake. Most of the values given in table 2 are contract costs of the work; however, the values given for both Los Angeles districts are estimates made shortly after the earthquake. The contractual costs in these estimates could be reduced if a less costly method of repair can be developed, or they may be increased if additional damage is discovered upon opening the damaged areas of the building for repairs.

No segregation was made in table 2 for contracts or estimates for minor repairs to pre-Field-Act school buildings and post-Field-Act school buildings; therefore, this $2.9 million loss applies to both pre and post-Field-Act construction. In order to obtain a clearer picture of the comparative performance of the two types of construction, it can be reported that the replacement cost of six pre-Field-Act school buildings damaged in the Los Angeles District amounts to an additional $10.3 million. Thus the total loss of pre-Field-Act and post-Field-Act public school buildings is $13.2 million.

The 1969/70 estimated value of all buildings and appurtenances (not including land cost) in the Los Angeles Unified School District amounts to $850 million, with an additional $100 million for equipment. Based upon these figures, the Los Angeles Unified School District had an estimated 1.3 percent loss of the present value of the buildings and appurtenances. Most of this was attributable to pre-Field-Act building damage.

Another interesting comparison can be made of the loss at school buildings within 5 miles of the Pacoima Dam. There are 19 public schools in the Los

Table 2. Estimate of cost of repair, rehabilitation, and replacement to school property and equipment, Los Angeles School Districts. (Data from the U.S. Department of Health, Education, and Welfare)

School district	Debris removal and clean-up	Minor repairs to buildings and site	Repair and replacement of equipment	Instructional supplies and materials	Textbook losses	Other losses
Los Angeles Unified	$47,408	$2,014,571	$7,112	$52,714	$724	$55,510
Los Angeles Community College	300	21,500	----	----	----	----
La Cañada Unified	----	3,139	745	49	----	----
Newhall Elementary	4,065	14,506	940	264	----	----
Pasadena Community College	537	16,215	----	----	----	----
Pasadena Unified	970	10,549	----	----	----	----
Saugus Union Elementary	----	35,641	512	----	----	----
Soledad-Agua Dulce Unified Elementary	100	18,931	----	----	----	----
Temple City Unified	92	7,167	150	40	----	----
Whittier Unified High	----	4,519	----	----	----	----
Beverly Hills Unified	----	10,887	----	----	----	----
Burbank Unified	2,677	12,828	193	487	----	----
El Segundo Unified	----	61,310	----	----	----	----
Glendale Unified	10,414	308,424	1,953	3,167	----	----
Glendale Community College	1,087	24,594	----	----	----	----
Wm. S Hart Unified High	3,400	133,494	1,595	1,766	----	----
Santa Monica Unified Junior College	----	----	----	----	----	----
Culver City Unified	----	----	----	----	----	----
Inglewood Unified	----	----	----	----	----	----
Lancaster Elementary	----	----	----	----	----	----
Westside Union Elementary	----	----	----	----	----	----
Palmdale Elementary	----	----	----	----	----	----
Sulphur Springs Union Elementary	3,390	38,725	47	50	----	----
TOTAL	$74,440	$2,737,000	$13,247	$58,537	$724	$55,510

SUM (includes damage to pre-Field Act buildings and post-Field Act buildings	$2,939,458
Allowance for replacement of six pre-Field Act buildings damaged	10,261,778
Total building loss	$13,201,236

Angeles Unified School District within 5 miles of the Pacoima Dam. The estimated costs for repair, clean-up, etc., amount to $1 million. This, too, includes losses at pre-Field-Act and post-Field-Act schools. The estimated value of the buildings and site improvements (exclusive of land) amount to $45 million. Therefore, within a 5-mile radius of Pacoima Dam, the public school buildings experienced a 2.2 percent loss of the present estimated value. An interesting dollar loss comparison can be made here. Steinbrugge and others (1971, p. 24) reported that, in an area somewhat comparable to the 5-mile radius of Pacoima Dam, there was a 6.6 percent loss in dwellings; that is, in the 12,000 dwellings investigated by the team, there were $12.4 million losses in a total dwelling value of $189.4 million exclusive of personal property losses and land value losses. A sampling of over 1000 dwellings by the Los Angeles County Assessor's Office revealed a 21.5 percent loss.

It should be mentioned here that, although there was considerable damage to pre-Field-Act public school buildings and some nominal damage to post-Field-Act public school buildings in the stricken area, no public school building collapsed from the San Fernando earthquake.

BUILDING DAMAGE EXAMPLES

Figure 1 shows the location of the public schools at the time of the earthquake and the other locations mentioned in this report. It should be noted that the public schools are well distributed around the epicenter of the earthquake and throughout the affected area.

Damage results from various sources and reasons. There are two types of damage. One type is "structural" damage and that, as the name implies, applies to the damage in the structure or the load-carrying members. The other type of damage is frequently termed "non-structural" damage. As that name implies, covers all other types of damage found in the finishes and treatments as well as mechanical and electrical devices. Basically, there are two sources of damage—one source is from the vibrations alone and the other from ground fracturing, separating, or thrusting, coupled with vibrational damage. Building codes generally do not provide for ground fracturing, separating, or thrusting. If such ground failures occur, the building certainly cannot restrict the whole surrounding geology from performing in its natural manner; however, under certain conditions, there are some design precautions which can be exercised to reduce the effects of such an event. Building codes, however, intend to provide minimum safeguards based upon economic considerations and the state of the art or level of knowledge. Although there have been great strides made recently in earthquake engineering, there is much more to be learned concerning this very complex subject. A few specific examples of the general

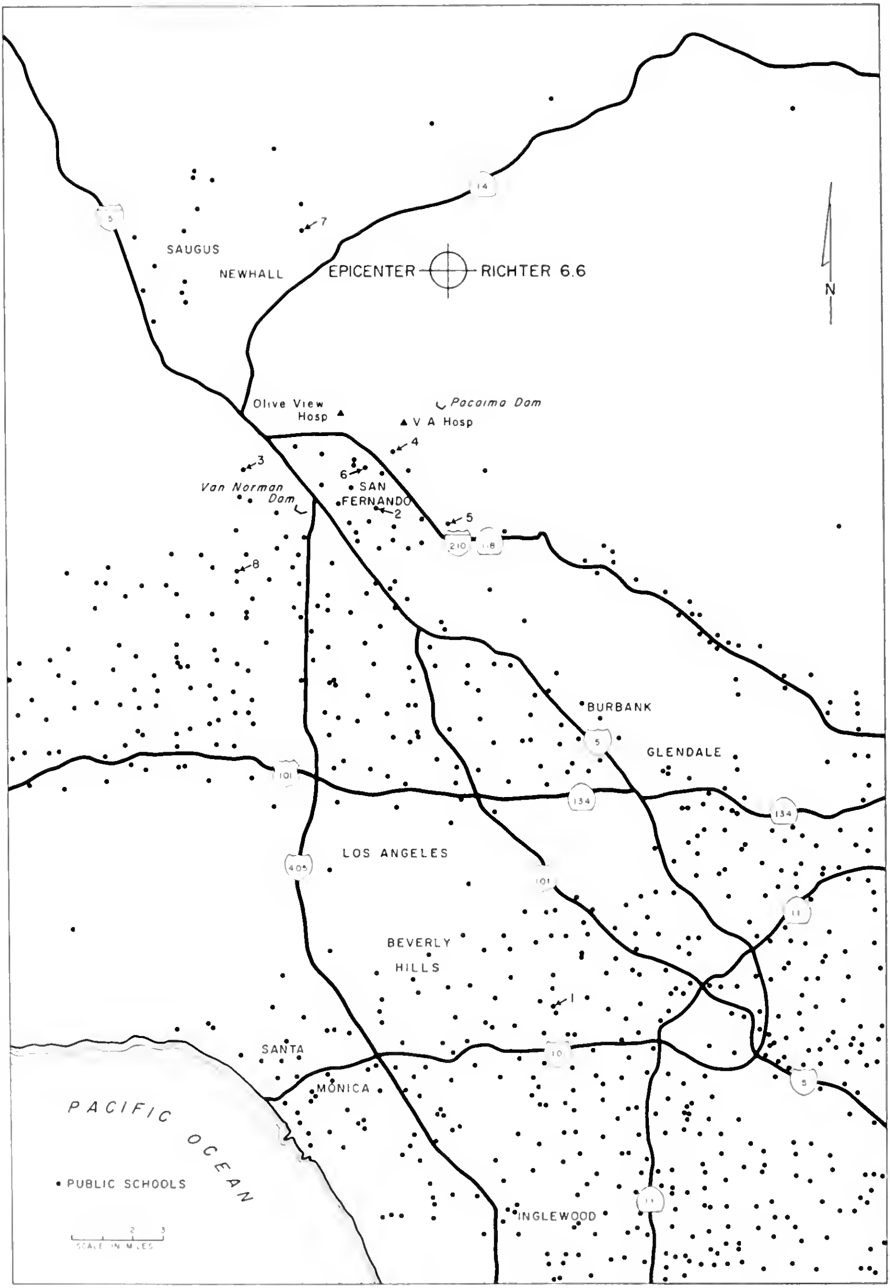


Figure 1. Location map showing public schools and epicenter of February 9 earthquake.

type of damage experienced by school buildings will be given. (Parenthetical number refers to location shown on figure 1)

Los Angeles High School

Los Angeles High School is more than 20 miles from the Pacoima Dam. (1) The main building (photo 1) on this high school site was a pre-Field-Act building constructed in 1917, contained about 200,000 square feet of floor area and was constructed of wood floors, concrete frames, unreinforced brick masonry exterior walls, unreinforced hollow clay tile interior partitions. Masonry was laid in lime mortar. The building was supported by spread footings. Two long sections of the parapet and adjacent brick veneer fell off one portion (photo 2). Portions of the debris fell through the lower wood roof to the floor below (photo 2). Other portions fell on the exit stairway and into the court yard area (photo 3). The exterior building walls were heavily cracked, as were building interior partitions; light fixtures fell to the floor; and equipment was thrown about. Typical interior wall damage is shown in photos 4 and 5. The walls of the chime tower were heavily damaged. If the earthquake had lasted a few seconds longer, there would have been much greater damage. This building was demolished at a cost of about $127,000; the replacement cost will be more than $8 million. There was no damage to the many post-Field-Act school buildings at this site.

Photo 1. Los Angeles High School. Parapet and veneer shaken off four-story portion of this pre-Field Act school building.

Photo 2. Los Angeles High School. Portion of brick parapet fell through roof into adjacent classroom wing.

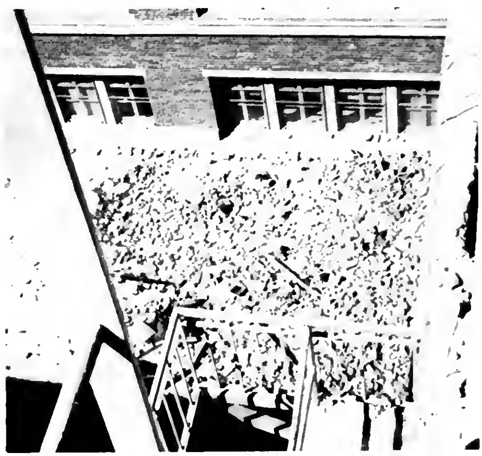


Photo 3. Los Angeles High School. Parapet debris in school yard.

Morningside Elementary School

Morningside Elementary School (2) is about 4 miles from Pacoima Dam and is comprised of both pre-Field-Act buildings and post-Field-Act buildings. One pre-Field-Act building constructed in 1917 was rehabilitated in 1964 to meet the requirements of the Field Act (photo 6). This building sustained damage amounting to cracks in the old and new walls; several roof anchors pulled loose; plaster was damaged throughout the building; and light fixtures fell. The

Photo 4. Los Angeles High School. Interior-partition damage at stairway.

Photo 5. Los Angeles High School. Brick and wall damage at exit door.

estimated cost of repair to this building was about $69,000.

The other pre-Field-Act building had not been rehabilitated. Masonry walls throughout the building were extensively damaged (photo 7). The parapets were on the verge of falling (photo 8). Light fixtures fell or were displaced. The cost to demolish this 13,000-square-foot building is estimated at about $13,000, and the estimated cost to replace it is about $442,000. The present value of the buildings and site improvements amounts to about $1.4 million.

Van Gogh Street Elementary School

Van Gogh Elementary School (3) is about 6¾ miles from the Pacoima Dam. This school was constructed in 1968 under the provisions of the Field Act. There was extensive ground cracking throughout the site and building (photo 9). Shortly after the earthquake, it was reported that the site would be abandoned; however, the site was examined geologically and the buildings were investigated structurally, resulting in the decision to repair the site and buildings and continue their use. The site is on the flank of a

Photo 6. Morningside Elementary School. Rehabilitated to meet the requirements of the Field Act.

Photo 7. Morningside Elementory School. Unrehabilitated pre-Field Act building. Typical interior-wall damage.

Photo 8. Morningside Elementary School. Pre-Field Act building. Parapet on verge of falling.

rather broad alluvial fan, and it is believed the ground displacement was due to liquefaction. Depth of the alluvium is unknown but exceeds 35 feet. The building, which is supported on several feet of recompacted soil or engineered fill, is wood frame supported by spread footings. Ground cracking caused the foundations and slabs on grade to crack (photo 10), as well as the walls and roof (photo 11).

One wood dragtie in the roof structure broke in tension where the slope of grain across the 2-x-6-inch beam was about 1 in 5 or 6. Light fixtures and plaster were damaged. The steel tube lunch-shelter columns were bent several inches out of plumb. A 4-foot-high retaining wall was rotated out of place, and the stem failed at the top of the foundation and at the level of the adjacent sidewalk. Estimated cost to repair the site and building was $104,000. The present value of site improvements and the buildings is projected to be about $1.2 million.

Photo 9. Van Gogh Street Elementory School. Diagonal crock in slab near rock; damage in the concrete steps beyond.

Photo 10. Van Gogh Street Elementary School. Footings cracked where ground cracked.

Photo 11. Van Gogh Street Elementary School. Underside of roof overhang damaged above ground cracks.

Hubbard Street Elementary School

Hubbard Street Elementary School (4) is the closest school to the Pacoima Dam; it is about 2 miles from the dam and less than a mile from the collapsed Veterans Administration Hospital. The ground was nominally cracked as indicated in photo 12. The buildings, which were constructed under the provisions of the Field Act, consist of classroom buildings, a multi-purpose building, and several bungalows, all of wood-frame construction. The primary structural damage at the site consisted of as much as 6 inches of lateral displacement of the wood-cripple-stud walls supporting the bungalows, causing the plywood to loosen, separating the entry porches, and breaking the gas lines. In several areas, acoustical tile fastened to the ceiling with adhesive, fell to the floor. Over half the stem-mounted light fixtures fell or were partially down. In general, the buildings were in good structural condition. The estimated cost for debris removal and cleanup was $2,300; the estimate for minor repairs to building and site was $37,600 and the estimate for loss in equipment was $1,800 for a total estimated loss of $42,000. The present value of site improvements and buildings is projected to be about $1.3 million.

Fenton Avenue Elementary School

Fenton Avenue Elementary School (5) is about 4 miles from the Pacoima Dam and about ⅜ mile from the Tujunga segment of the San Fernando fault zone. It is also about a quarter of a mile from the Pacoima Lutheran Hospital, a recently constructed building which was so damaged that it was vacated and later demolished. The Fenton Avenue School site showed some nominal ground cracks. There was very little damage to the school buildings. All buildings were built under the provisions of the Field Act and consist of classroom buildings (photo 13), a multi-purpose building, and bungalow buildings. All construction was of wood framing. Damage consisted of broken light fixtures, some plaster cracking, and slight pounding between the arcade steel column framing and the wood building construction (photo 14). Bungalows were displaced as much as 4 inches laterally. There was essentially no structural damage. The cost estimate for minor repairs to buildings and site amounted to $4,600; the cost for repair of movable equipment was $20; and the cost for textbooks and other losses was $900, for a total estimated loss of $5,520. The present value of the buildings and site improvements amounts to over $1 million.

Sylmar High School

Sylmar High School (6) is about 3¼ miles from the Pacoima Dam. The site had a great deal of ground crackings and cracking of the foundations and slabs on grade. It is estimated roughly that the site shortened about a foot. The school was all post-Field-Act construction. All the buildings in this high school plant are of one-story wood construction, except the gym-

Photo 12. Hubbard Street Elementary School. Repairs being made to underpinning of a bungalow.

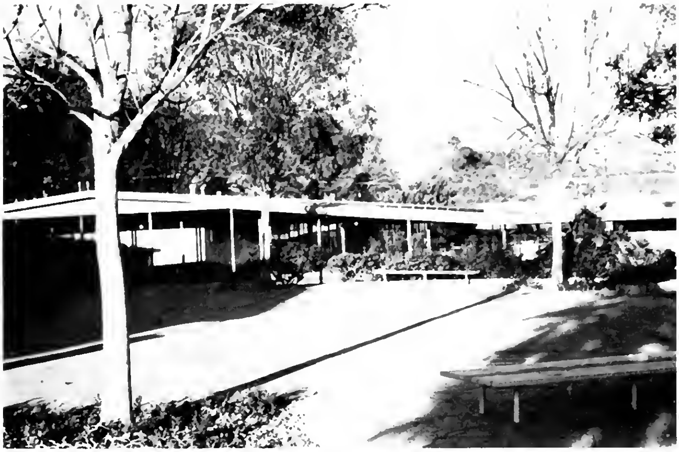


Photo 13. Fenton Avenue Elementary School. Essentially no damage.

nasium which is a prestressed concrete folded-plate roof, with walls of reinforced concrete, resting on concrete piles. The gymnasium floor had some settlement and two roof beams were spalled a bit at a cross beam used to support gymnastic equipment (photo 15). This cross beam was added after the building was built and not installed under Field Act provisions. No damage could be found to the gymnasium piles.

There was considerable damage due to ground breakage. Many sidewalks and slabs on grade were broken throughout the site (photo 16). Equipment was thrown about; light fixtures fell to the floor in several rooms; plaster was cracked and fell; and arcades pounded together at the joints and library books were thrown from the shelves (photo 17). A large retaining wall rotated about 8 inches. A flag pole bent at the first lower welded point (photo 18), and a flood-light pole bent at the upper welded joint. This site sustained the greatest amount of damage which was primarily due to the ground cracking and displacement, of any post-Field-Act construction. The estimated cost for the repairs to the building and site was about $485,000; the cost for debris removal was

Photo 14. Fenton Avenue Elementary School. Slight damage to stucco where lunch-shelter roof joined multipurpose building.

Photo 15. Sylmar High School Gymnasium. Damage to prestressed concrete beam at gymnastic equipment cross beam.

Photo 16. Sylmor High School. The site hod considerable ground fissures.

about $2,000; and the cost for the equipment repair or replacement was about $35,000. This site was used by the Sylmar Disaster Committee for several meetings and by the Los Angeles Department of Water and Power as a temporary garage and storage facility for a month following the earthquake. The present value for the buildings and site improvements is a bit over $5 million.

Soledad Canyon Elementary School

Soledad Canyon Elementary School (7), in the Sulphur Springs Union Elementary School District (all other sites specifically mentioned in this report are within the Los Angeles Unified School District), is about 7 miles northwest of the Pacoima Dam in the Newhall-Solemint area and about 2½ miles from the epicenter. All buildings were built under the provisions of the Field Act. Roof framing was of wood and steel; the exterior was of reinforced, grouted, brick masonry. The site contained some ground cracks (photo 19). Light cracking occurred at the corners of the reinforced, grouted, brick-masonry walls where steel beams were anchored to these walls (photo 20). When repairs were made to these beam-wall connections, it was noted that the construction details did not conform to the details shown on the plans; that is, certain welds and anchor bolt ties were omitted. Ceiling and light fixtures became unraveled (photo 21). There are five schools in this school district. All school buildings are post-Field-Act construction, and the total contractual cost for the repair of damage in this district amounted to $42,212.

Patrick Henry Junior High School

Patrick Henry Junior High School (8), is about 8½ miles southwest of the Pacoima Dam. All buildings

Photo 17. Sylmor High School. Library books thrown off shelves. Note uniform depth of books.

Photo 18. Sylmar High School. Flagpole bent at the first welded joint above the ground.

Photo 20. Soledad Canyon Elementary School. Damage in reinforced grouted brick masonry wall below roof beam at left.

on this site were built under the provisions of the Field Act. The paved playground area displayed little cracking, indicating that the soils were relatively stable (photo 23). The reinforced concrete two-story arcade between classroom wings was damaged at the top of the column (photos 24 and 25). The column beam connection with the greatest amount of damage is shown in photo 25. This arcade has now been demolished. Some ceiling tile in the multi-purpose building fell to the floor and the light-gauge steel penthouse structures housing the mechanical equipment were damaged slightly. A handrail on a second floor passage was broken at the intersection of the building and a cross passage. The estimated cost for repairs to

Photo 19. Soledad Canyon Elementary School. End elevation; ground cracks.

Photo 21. Soledad Canyon Elementary School. Damage to ceiling and light fixture in the multipurpose room.

Photo 22. Soledad Canyon Elementary School. Damage to light fixture in classroom.

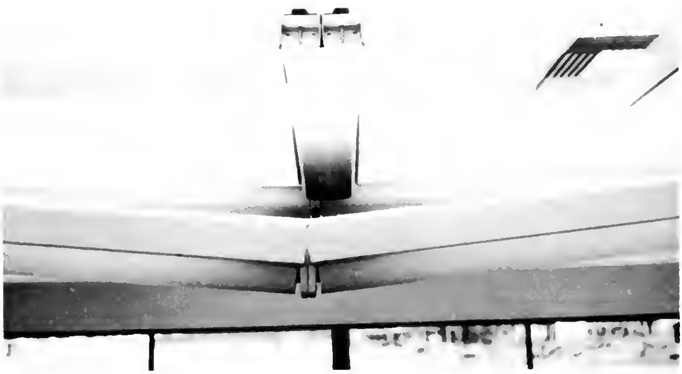


Photo 23. Patrick Henry Junior High School. End elevation of two classroom wings.

Photo 24. Patrick Henry Junior High School. Two-story arcade between classroom wings. Temporary wood bracing was added.

the building and site amounted to about $24,000. The present value for the buildings and site improvements amounts to about $4.2 million.

CONCLUSIONS AND RECOMMENDATIONS

This earthquake clearly brought out the difference in the performance of pre-Field-Act buildings and post-Field-Act buildings. Obviously, pre-Field-Act buildings can be very hazardous. Fortunately, the strong earthquake motion for this moderate earthquake lasted only about 12 seconds, as recorded at Pacoima Dam. Much greater damage would have occurred if the duration of motion had been longer or if the epicenter had been closer to the buildings.

Although this report is directed to the performance of public school buildings in this earthquake, many buildings constructed in the era prior to the enactment of the Field Act (which applies only to public school buildings) were constructed to the same or similar standards and these other buildings could be equally hazardous. In the interest of public safety, all hazardous buildings should be examined and corrected by competent personnel.

If less non-structural damage is desired in such items as light fixtures, ceilings, glass, and other architectural treatments as well as mechanical or electrical equipment—more consideration must be given to the internal design and construction of such fixtures and to their methods of anchorage. Such damage and hazards can be reduced with little additional cost to the total project.

Much more research is needed in the field of earthquake engineering. There is much work to be done. Especially needed are more strong-motion earthquake records on all types of geologic and soil conditions *, and in engineering structures; also needed is the construction of a complete three-component earthquake-motion platform to reproduce strong earthquake motion. Such facilities as the "shaking platform" will permit testing large assemblies of various types of man-made construction under completely controlled conditions. It is also important to visit sites of strong earthquake motion with the view of revising and enforcing building regulations.

One of the reasons the post-Field-Act public school buildings performed so well was the require-

* The State's Division of Mines and Geology has now started a comprehensive program of instrumentation under the 1970 law: "Strong-motion Instrumentation Program" . . . Editor

Photo 25. Patrick Henry Junior High School. Opposite side of column in foreground of photo 24.

ment for continuous inspection to assure that the actual construction complies with the designer's intent. This is performed in two ways as required by the Field Act. One, is by the architect and structural engineers who periodically visit the building during all stages of construction to assure that their design intent is carried out, and the other is by the inspectors at the project who continuously inspect for compliance with the contract documents. Good building regulations and plans are valueless if construction does not conform to their requirements. Good inspection assists the contractor in performing his duties and provides assurance to the owner. Inspection of buildings after the San Fernando earthquake revealed errors in construction which indicate that inspection procedures must be improved or applied more consistently. Another reason the post-Field-Act buildings performed well is the required independent review of the plans and specifications, by competent personnel, for conformance with the adopted building regulations. Actually, there is very little difference between the building code adopted for public school buildings and those codes adopted by local agencies. There is, however, a difference in enforcement.

Some structural, vibrational damage occurred which substantiates the point that the adopted building regulations are not overly conservative. Interested technical groups are studying the effects of the earthquake in order to propose revisions to the building regulations. Several code revisions have been or are in the process of being adopted by various enforcing agencies.

CHAPTER 27

Highway Damage in the San Fernando Earthquake[1]

by California Division of Highways[2]

The area affected by the earthquake lies in the northwestern San Fernando Valley immediately south of the San Gabriel Mountains in the Transverse Ranges of Southern California.

Major road damage was concentrated within an area of 12 square miles in the northern San Fernando Valley and involved about 10 miles of freeway. The heaviest concentration of road damage occurred at the Route 5/210 (Golden State/Foothill Freeway) Interchange and along the completed 5-mile portion of Interstate Route 210. Portions of Interstate Routes 5 and 405 (San Diego Freeway) and State Routes 2 and 14 also sustained moderate to heavy damage.*

FREEWAY DAMAGE

On Route 5, damage extended from the Mission separation structure to the Santa Clara River overhead structure. The heaviest concentration of damage occurred between the Route 5/405 Interchange and 5/14 Interchange. Damage to the roadway consisted of settlement at bridge approaches and buckling, heaving, and cracking of concrete pavement at various locations. Fill was distorted in some of the higher bridge approaches, and two slides occurred in cut slopes between Balboa Boulevard and Route 14. Damage to structures ranged from minor cracking and spalling of joints to total destruction of several bridges. The bulk of the damage occurred within the limits of two construction contracts, one that included the Route 5/14 Interchange and a second that included the Route 5/210 Interchange.

On Route 14, the damage extended from the Route 5/14 Interchange to the Santa Clara River. The major damage was concentrated in the Route 5/14 Interchange area which was under construction at the time of the quake. There was damage to all structures, again ranging from minor cracking and spalling to the loss of complete portions of bridges. The damage on Route 14 at the easterly end consisted of settlement of approaches, offsetting of alignment, and minor cracking and spalling of both the Solemint and Santa Clara River Bridges. There was no particular damage to the roadway on Route 14 (the new freeway roadways for this project had not been completed).

On Route 210, there was damage to both roadway and structures throughout the completed portion of this freeway, which extended from its intersection with Route 5 to the Maclay Street separation structure. Throughout this total area, the freeway settled on a somewhat uniform grade line. The effect was obvious at bridges, where the settlement ranged from 6 inches to approximately 2 feet, with the greatest distortion on the easterly end of the project. Pavement was buckled, broken, and separated for several hundred feet each side of the structures. The sides of fills were distorted. Structural damage ranged from minor damage to wing walls and slope paving to rotation and settlement of abutments, spalling and cracking of columns, and displacement of wing walls. The street sections heneath the various undercrossings had damaged curbs, sidewalks, slope paving and some cracking of roadway sections.

On Route 405, damage extended from San Fernando Mission Boulevard undercrossing to the intersection with Route 5. Damage consisted of settlement at bridge approaches, buckling and breaking of pavement as on the other routes, and relatively minor damage to the bridge abutments and wing walls.

On Route 2, the damage was confined to a series of small slides although fill settled and pavement was cracked in one place. The damage extended from approximately 2 to 6 miles east of La Cañada.

Summary of foundation conditions and types of construction

Freeway or Interchange	Principal foundation condition	Principal type of construction
5/14	Bedrock, marine sediments	Cut
5/210	Alluvium	Fill
5/405	Bedrock, continental sediments	Cut
Route 210	Alluvium	Fill
	(Minor amount of bedrock, continental sediments)	Cut
Route 5 (south of 210)	Alluvium	Fill
	(Minor amount of bedrock, continental sediments)	Cut
Route 5 (north of 210)	Bedrock, marine and continental sediments	Cut
	(Minor amount of alluvium)	Fill

[1] Manuscript submitted by Donald L. Durr, California Division of Highways, September 7, 1971.

[2] Prepared by the Foundation Section, Materials and Research Department. The work was done in cooperation with the U.S. Department of Transportation, Federal Highway Administration. The findings and opinions expressed in this report are those of the authors and not necessarily those of the Federal Highway Administration.

* For locations of highways, see figure 1 in Chapter 20 of this volume.

Emergency repair work and construction of detours through the damaged area cost about $1,640,000. Permanent restoration of the freeway facilities will cost about $12,100,000 including about $6,400,000 to restore the bridges and $5,700,000 for all other facilities. These figures do not include engineering costs and may be increased if hidden damages are uncovered during reconstruction.

CUT SLOPES

Several slides in cut slopes were caused by the quake. The three largest slides occurred on construction projects but would have had little effect on the traveled way even if the road had been in service. One exception was a bedding plane failure on Route 5. This slide, shown in photo 1, would have blocked Ramp "V" which is designed to connect southbound traffic from Route 14 with San Fernando Road. The other two slides (one of which had previously shown a tendency to slide) developed in the upper portions of the slopes and did not collapse completely. Moderate to large volumes of earth materials were involved in the three larger slides.

Smaller slides were much less spectacular. Some moved so slightly that they were not detected during the initial damage survey. These slides, however, did affect the traveled way by thrusting the pavement sections up, causing diagonal and longitudinal cracks and raising portions of the pavement noticeably.

The behavior of cut slopes depended upon the type of material in the slope. For example: slopes in dense, stiff, brittle materials (silts and silty sands containing enough nonplastic fine material to have become desiccated enough to appear cemented) fractured and shattered badly over distances of 20 to 30 feet behind the top of the cut and often in the face itself. Examples are shown in photos 2 and 3. Materials of moderate density and a slightly greater moisture content showed far fewer cracks and no shattering. Often only one or two large cracks were found along the

Photo 1. Cut slope failure on Route 5 between route 5/14 and Route 5/210 Interchanges

Photo 2. Cracking along top of cut slope on Route 210.

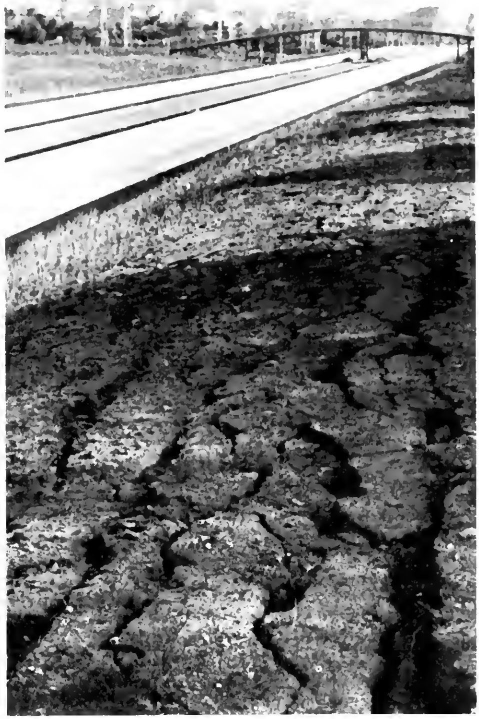


Photo 3. Cracking along top of cut slope on Route 210.

slope top. Slopes in loose materials cracked behind the slope (where the surface was desiccated) in a parallel pattern, and the slope moved successively in small amounts at each crack toward the unsupported surface. This type of material also sloughed and slumped in the slope face.

Overall cut-slope performance was considered very good from the standpoint of slide development—most slopes did not fail, even during strong ground motion—although three major slides did occur in very large cuts. The potential damage from large-cut slope failures is very real, however; and large cuts should be evaluated by geologists and engineers for their failure potential in high earthquake-risk areas.

EMBANKMENTS AND FILL DAMAGE

Embankments were damaged in several ways, including shear failure, subsidence due to densification, spreading, and longitudinal and transverse cracking caused by ground motion.

Fill damage caused by foundation soil response to the earthquake consisted of (1) subsidence due to the more pronounced densification of looser underlying sands and gravel and (2) slipouts initiated in the weaker, fine-grained soils. No reasonable treatment outside the scope of current procedures is available for these problems. For example, the foundation failure on Route 5 resulted in a vertical subsidence of only 1 foot and even less lateral movement. The lack of greater movement indicates that the foundation material had good strength prior to the quake.

Differential movement at abrupt cut/fill contacts resulted in transverse cracks and vertical displacements across the pavement. For very shallow fills, the problem was minor.

The type of damage most often observed was subsidence due to vibratory densification by earthquake shaking of fill and foundation materials, both of which consist of nonplastic silty, gravelly sands except at a few locations. Subsurface soils (earth materials) were densified, not only under fills, but in areas outside the influence of added fill weight. Greater densification did occur under the fills, however, especially at locations where the materials were very loose prior to the quake. Generally, earthquake densification of foundation materials resulted in much greater fill subsidence than densification of the fill itself because the deposits of alluvium affected by the ground vibrations were in a looser pre-quake condition than the fill and are substantially thicker at most locations than is the fill.

The contribution of subsurface soil (natural foundation materials) densification to fill subsidence can easily be detected at locations where rigid inclusions in natural ground pass under the fills. This type of differential subsidence occurred at the Polk Street/210 Interchange and on Route 5, just north of Rinaldi Street. At both locations, a reinforced-concrete-box drainage channel was crossed by fills about 25 feet thick. Differential subsidence resulted from the earthquake, and a ridge or high area in the roadway surface was created over the nonyielding inclusion. As the fill on either side of the rigid element subsided, shear cracks were formed in the fill slope, beginning at the toe and extending up the slope face. Where the movement was relatively small, the cracks extended only about half way up the slope. As total subsidence increased, the cracks continued to develop and extended across the roadway. Some were and some were not reflected in the pavement section but could be observed in unpaved medians and shoulders.

Some spreading of fills near structures was associated with densification within the fill proper due to the tendency for movement toward unsupported surfaces. This type of spreading in the fill proper was minimal, fairly uniform and confined for the most part to the ends of approach fills under bridges. Fill spreading caused by lateral movement in foundation soils during densification was observed at a few locations but was limited in amount due to the inherent high shear strength of foundation soils. This resulted in bulging in the lower half of fill slopes and formation of longitudinal tension cracks in the upper half as the fill subsided differentially in a plane normal to centerline. Enough lateral movement near the fill toe at some locations caused minor thrusting of inside curb and gutter sections of freeway ramps. Also, as the fills subsided, the lateral component of slope paving movement sheared and rotated the curbs along the surface streets under the freeway structures, as shown in photo 4.

Photo 4 Concrete curbs broken by lateral movement of slope paving during fill movement.

Photo 5. Vertical and horizontal offsets in concrete pavement slabs caused by shear failure in fill material.

Slipouts (earth slides in embankments) varying in size and amount of movement occurred in fills at several locations. Maximum movement was small (inches, or a few feet) but was sufficient to cause differential vertical displacements at longitudinal joints in pavement slabs (photo 5), diagonal cracks across the pavement at the flanks, and minimal thrusting near the toe. Larger movements were prevented by the high strength of fill and foundation materials. The larger slipouts underwent the greatest movement and were observed to have occurred in long fills, all of which were 20–30 feet high. The smaller slipouts often underwent very little movement and in some cases were difficult to detect. They usually occurred in fills crossing small ravines and developed because of differential response by fill and natural ground. Consequently, lateral limits of these slides generally followed the cut/fill contact.

Three fill slipouts caused by plastic-type movements in fine-grained compressible foundation soils occurred within one fairly small area on Route 5 just east of the Lower Van Norman Lake. These slipouts involved more vertical and lateral movement than those occurring in fills only. The portion of fill undergoing movement dropped a maximum of 1 to 1.5 feet. Lateral movement was somewhat less due to the rotational effect, but large cracks up the fill slope were formed at the flanks. These slipouts covered a larger portion of the roadway than those in fills only.

The over-all effect of fill subsidence was a loss in roadway profile at cut/fill contacts and bridges. In some cases, especially at bridges, this abrupt change in profile was large enough to prevent traffic from using the road. In some other cases, the bump at bridge approaches was accentuated but traffic could still use the facility.

Damage to fills with respect to shear failure was considered minor despite the fact that three slipouts did develop in very good material. This suggests that high fills should be evaluated for their failure potential in high earthquake-risk areas. Subsidence due to densification within the fill cannot be eliminated entirely and can be reduced only by keeping fill heights as low as practical. It is very doubtful whether increased compaction beyond that presently required would be economically desirable.

BRIDGE APPROACHES

Widespread settlement at bridge approaches occurred on all freeways surveyed for damage. This problem varied according to distance from the heavily damaged area and stage of construction of the road. For example, on existing Routes 5 and 405 south of the Mission Hills, the problem clearly affected the "rideability", especially on Route 405, even after asphaltic concrete patches were hastily placed at approaches to relieve the abruptness of changes in profile. An important factor is that settlement was not so great as to prevent traffic from using the facilities without further repair work. The effect was much worse on Route 210, which was closed to traffic for quite a long period, as there were differences in roadway profile in excess of 1 foot at some bridge approaches (photos 6, 7, 8).

Settlement at approaches is the result of subsidence of embankments and structural backfill material. Although the backfill material subsides more due to densification than the fill itself, it is usually the fill and not the structural backfill that is the principal cause of the problem. This is because of the bridging action of the reinforced-concrete approach slab which is supported at the bridge deck by the paving notch and at its other end by fill material. The slab acts as a ramp up to and down from the bridge deck. The fact that the slab is unsupported by the structural backfill becomes important only if the slab (1) falls off the paving notch, (2) fails by cracking, or (3) is of insufficient length to provide adequate bearing area on the fill. If any of the three conditions exists or occurs, the situation is worsened and it first appears that the structural backfill only is entirely responsible for the problem instead of merely contributing to it.

THE PAVEMENT SECTION

Damage to the pavement section was found to depend almost entirely on the response of underlying materials to the ground motion and shocks generated by the quake. The most prevalent types of damage consisted of lateral and longitudinal separation between

Photo 6. Subsidence of bridge approach slab in the Route 5/210 Interchange area.

portland cement concrete (PCC) slabs at joints, differential vertical movement and resulting loss of pavement plane, transverse and diagonal cracking, and buckling at compression zones.

Separation between slabs with no detectable loss of constructed roadway plane was usually small and resulted from the response of fills to ground shaking. Some of the slabs separated by moving over the cement treated base (CTB) which remained uncracked. Other of the PCC slabs and CTB remained bonded together but moved due to cracks developed in the CTB. Separation without crack development in the CTB probably resulted from ground shocks sufficiently large to break the bond between the slab and base. This type of separation was infrequent since in most instances slab separation resulted from another type of damage or response.

Slab separation was generally accompanied by differential vertical movements over areas of various sizes. Actual relative vertical and horizontal movements between any two adjacent slabs were often quite small and, at some locations, even difficult to observe except from certain vantage points. Nevertheless, the paving plane was disrupted and could be felt when driving over the affected slabs at freeway speeds. These differential vertical movements occurred mostly in fill sections where the underlying fill material had subsided and created a dip, but some were noted in cut sections where the slabs had been raised due to an upthrusting action at the toe of potential slides involving the cut slope.

Slab separation accompanied by differential vertical displacements along longitudinal joints was noted at a few locations in fill sections. These were locations of well-delineated slipouts within the fill. If enough movement had occurred within the slipout delineation, diagonal cracks across slabs were in evidence.

Slab cracking at locations other than joints resulted from relative movement along the contact between cut and fill. Where original ground was very steep, movement was practically vertical and no differential horizontal movement along the crack was noted. Separation along joints was noted at some places but was apparently absent at others.

Diagonal cracks not associated with slipout delineations resulted from differential lateral movement of underlying materials such as the Juvenile Hall slide. This type of cracking was generally accompanied by rotational-type slab separation at joints on either side of the diagonal shear crack.

The separation of slabs in the vicinity of separation structures is believed to have been partly caused by the action of the structure being transmitted through the approach slabs to the pavement slabs, especially near those structures that experienced the more violent motion.

The remaining type of damage to the pavement section consists of compression buckles (photos 9, 10, 11). This phenomenon occurred almost exclusively in at-grade sections, the one exception being in cut along the line of contact between bedded sediments and alluvium. This type of damage is believed to result from compressional shortening within natural ground.

Faulting due to tectonic activity resulted in slight-to-moderate road damage. The San Fernando fault zone, for example, crossed routes 210, 5, and 405

Photo 7. Settlement and offset of bridge approach fill on Route 210. Note ramp effect of approach slabs.

Photo 8. Settlement of bridge approach fill on Route 210.

almost normal to roadways at locations sufficiently removed from separation structures that no damage to bridges resulted. The fault crossed Routes 5 and 405 immediately south of their junction (just east of the Lower Van Norman Dam), where both roadways are in cut, and resulted in very minor breakage in the pavement section. The thrusting effect, however, did disrupt the pavement profile as the north side of the fault break moved up relative to the south side. The break in roadway profile was not serious and was feathered in fairly easily with asphalt cement (AC) patching. The fault crossed Route 210 about 550 feet west of the Maclay Avenue undercrossing at a location where the roadway was almost at grade. Upthrusting of the north side was more pronounced than at the Routes 5 and 405 fault trace, and a much wider zone was affected as shown in transverse cracks in pavement slabs and separation and vertical displacements of slabs at joints. Damage was more severe than at the Routes 5 and 405 fault trace due to the greater relative vertical movement at the main fault trace and the longer lengths of pavement within the fault zone.

Only two locations on Route 14 roadbed settled sufficiently to require repair work: namely, the approaches to the Solemint Overhead Bridge and the Santa Clara River Bridge.

Damage to Foothill Boulevard consisted of numerous cracks of varying width in the AC pavement; vertical displacement at AC pavement cracks; broken sections of curb, gutter, sidewalk, and driveways; minor cracking and spalling of catch basins; and drastic upheaval of the pavement, curb, gutter, and sidewalk at two locations. Some of the damage was caused by surface fault displacement; and some, by failure of embankments or cut slopes.

DRAINAGE STRUCTURES

Damage to drainage structures was largely dependent on the response of earthworks in and under which they were constructed. Reinforced-concrete boxes and pipes sustained cracks and joint separations ranging in size from hairline to one or more inches, exposing reinforcing steel in many cases. Corrugated metal pipes were frequently distorted in shape but generally remained structually intact. A frequent but

Photo 9. Compression buckles in concrete povement on Route 210.

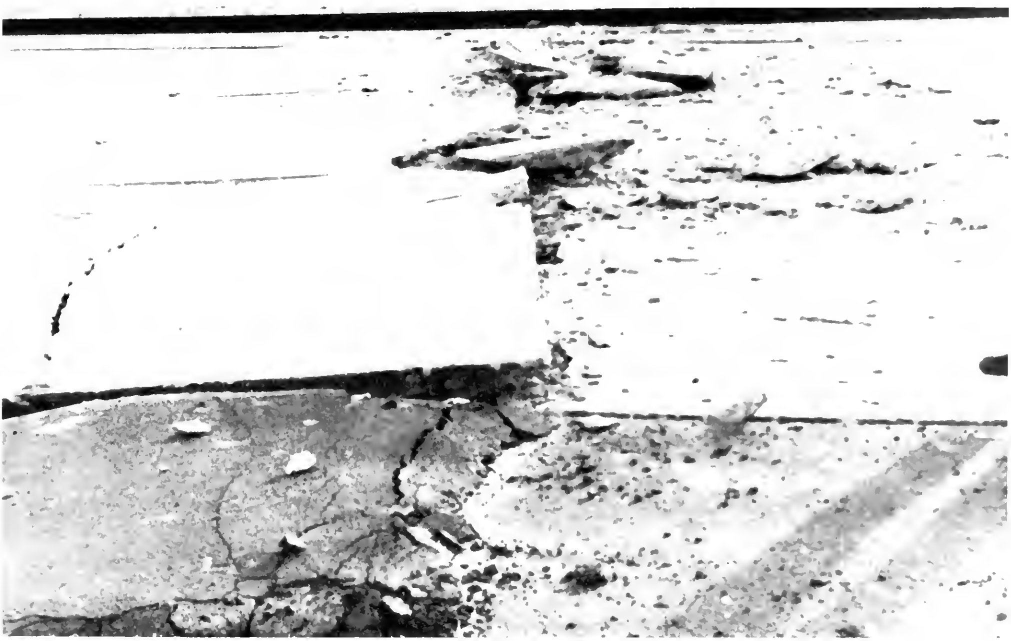


Photo 10. Spalling ond overriding concrete povement slabs on Route 210.

Photo 11. Compression buckle in asphaltic concrete ramp pavement on Route 210.

fairly minor damage observed was cracking in concrete headwalls, as shown in photo 12.

One of the most serious problems involving damage to drainage structures was differential movement which affected invert profiles. At most locations of pipes under fills, the sags in profiles resulted from foundation subsidence. At some locations it appeared that flow directions may have been reversed.

Inspection of major drainage structures in the earthquake affected area on Routes 5, 405, 210, and 14 revealed considerable damage resulting in hairline cracks longitudinally and transversely or peripherally due to seismic effects and disturbance of soils. The distress in the embankments, due to severity of the earthquake disturbance, caused excessive stresses on these structures and resulted in damage to reinforced concrete pipes, boxes, and inlet structures.

Inspection of the reinforced-concrete boxes showed certain similarities of distress. There were three and sometimes four longitudinal cracks in the range of 0.002-inch and 1/6-inch width going down the middle of the exterior walls and at the "spring" line, half way above the invert. There were ¼-inch and 3/16-inch cracks at the top and bottom of the exterior and middle walls of boxes, and spalling with exposed rebar was noticeable at several of the joints.

Similarly, there was considerable hairline cracking in the pipe culverts. Most of the cracking was nearly horizontal (continuous) about 3 or 4 feet above the invert. Both sides of the pipe were cracked. In addition, there were numerous transverse cracks extending above and below the horizontal cracks at almost every pipe joint.

At the Route 5/210 Interchange area, an 87-inch reinforced-concrete pipe was fractured to the extent that the reinforcing steel was exposed. A 208-foot length of the pipe was severely damaged, requiring a protective steel liner plate inside. This damaged portion had spalling with rebars exposed, twisted, and/or sheared. Cracks varying from 3/16- to ⅜-inch width

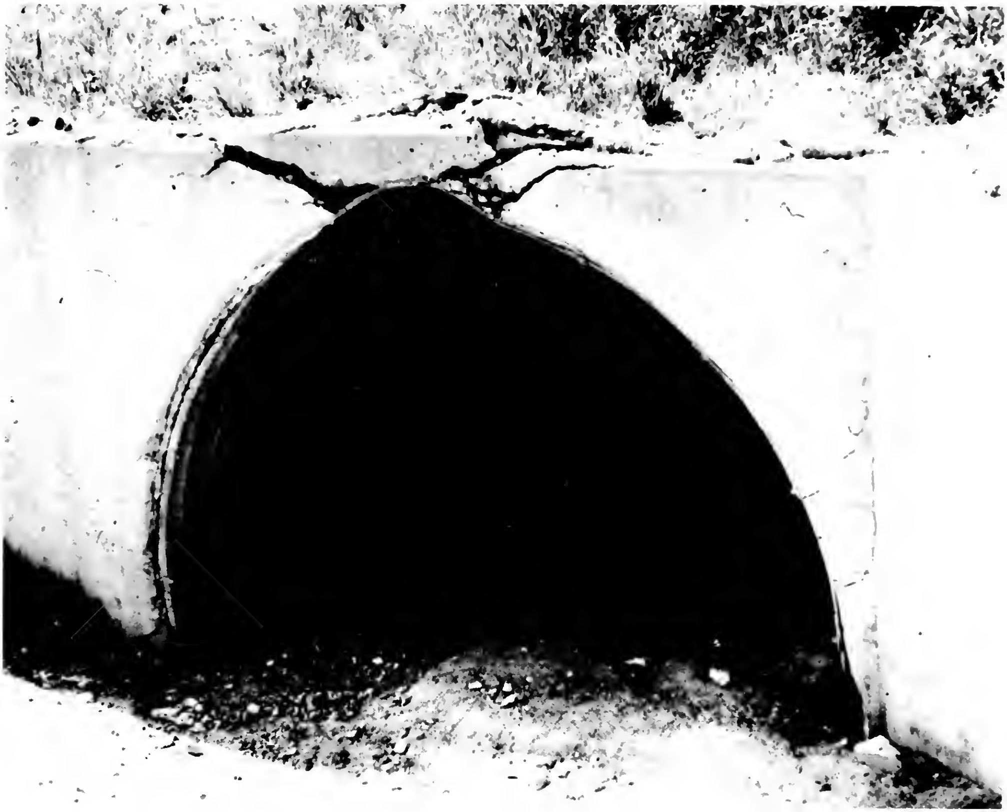


Photo 12. Fractured culvert headwall on Route 5.

with displacement as much as 1½ to 2 inches was noticeable at the joints. The remaining portions of the pipe could be repaired by injecting epoxy adhesive under pressure into the cracks and epoxy grouting the spalled transverse joints.

A 42-inch corrugated steel pipe also sustained severe joint separation in this area. It was believed that this pipe could be repaired without replacement. Several of the drop inlets in the area were badly cracked, and some were tilted to the extent that the connecting pipes were broken. Several of the drop inlets and connecting pipes appeared to require replacement.

A 39-inch reinforced-concrete pipe near the Olive View Hospital on Route 210 was severely disjointed and offset. Several vertical corrugated-steel pipe risers from cross culverts to drop inlets were badly distorted, although it appeared that only one would require replacement.

Inspection of an 84-inch unreinforced, cast-in-place concrete pipe, located to the east of Route 5 and south of Roxford Avenue approximately 35 feet east of the toe of the freeway fill, revealed considerable damage due to the soil disturbance. Cracks as wide as ⅜ inch were noticeable in the 4, 10, 2, and 7 o'clock positions. The inside surface of the pipe was dislocated with ¼- to ¾-inch offset along these fractures. A length of 600 feet was badly damaged and appeared no longer serviceable. At all other locations, the existing pipe could be salvaged by epoxy injection and spot patching.

CHAPTER 28

Damage to Highway Bridge Structures[1]

by J. Penzien[2] and R. W. Clough[3]

INTRODUCTION

This paper is based on a report entitled "Observations of the Damages of Highway Bridge Structures, San Fernando, California, Earthquake of February 9, 1971", prepared by the authors in April 1971, at the request of the Office of Research, Structures, and Applied Mechanics Division, Federal Highway Administration, Washington, D.C., for submission to the Division Structural Engineer, Federal Highway Administration, Sacramento, California.

As the field investigation was carried out on 12 and 13 February 1971, 3 and 4 days following the earthquake, clearance and demolition had considerably changed damage patterns. For this reason, this report is not a complete documentation of the damage observable immediately following the earthquake.

The purpose of this paper is to give a general overview of the damage to bridge structures caused by the earthquake and to evaluate some of the damage as it relates to design considerations.

INTENSITIES OF GROUND MOTION

Although the earthquake was of moderate magnitude, accelerograph measurements and the observed damage to structures indicate that intensity in the immediate vicinity of the epicentral area was probably near the upper-bound level for earthquakes; i.e. peak accelerations of the order of 0.6 g.

Since intensity decreased rapidly with distance from the epicenter, it is difficult to assess the intensities at the locations of the damaged highway structures; such assessment will most likely be made as soon as all recorded strong motion accelerograms have been processed and analyzed.

OBSERVED DAMAGE

Golden State Freeway (Interstate 5) and Foothill Freeway (Interstate 210) Interchange. The general arrangement of bridges and overcrossings at the interchange of Golden State Freeway and Foothill Freeway is shown in figure 1.

Approaching this interchange from the east along the Southern Pacific Railroad, one first reaches the collapsed overcrossing [3]* which carried northbound traffic from the Golden State Freeway onto Foothill Freeway. Photo 1 shows this overcrossing and the adjacent box girder span.

Photo 1. Overcrossing at the Golden State Freeway and Foothill Freeway interchange [3].

Two possible causes of collapse of this overcrossing were (1) the large vibratory motion induced in the super-structure by the high-intensity vertical and horizontal ground acceleration and (2) the relative ground displacement between abutment and column supports. Unfortunately, it was very difficult to assess the relative importance of these two causes.

In the background of photo 2 is the damaged San Fernando Road overhead [2] which is located at the intersection of the Golden State Freeway and the Southern Pacific Railroad. The central section of this bridge (original freeway) was built with steel girders and a reinforced concrete deck while the two outside sections (widened freeway) were built entirely of reinforced concrete. During the earthquake, the central section fell off one of its supports and was damaged. The outside precast prestressed concrete sections remained in position but had to be removed after the earthquake to provide access along the railroad.

Photo 3 presents a close-up view of this bridge at the same location where the simple span crossing the railroad (front foreground) had been removed. In the background of this photo, one can see the precast pre-

[1] Submitted for publication September 20, 1971.

[2] Professor of Structural Engineering; Director Earthquake Engineering Research Center, University of California, Berkeley.

[3] Professor of Civil Engineering, University of California, Berkeley.

* Numbers in brackets refer to identification numbers in figure 1. These identification numbers also appear in figure captions.

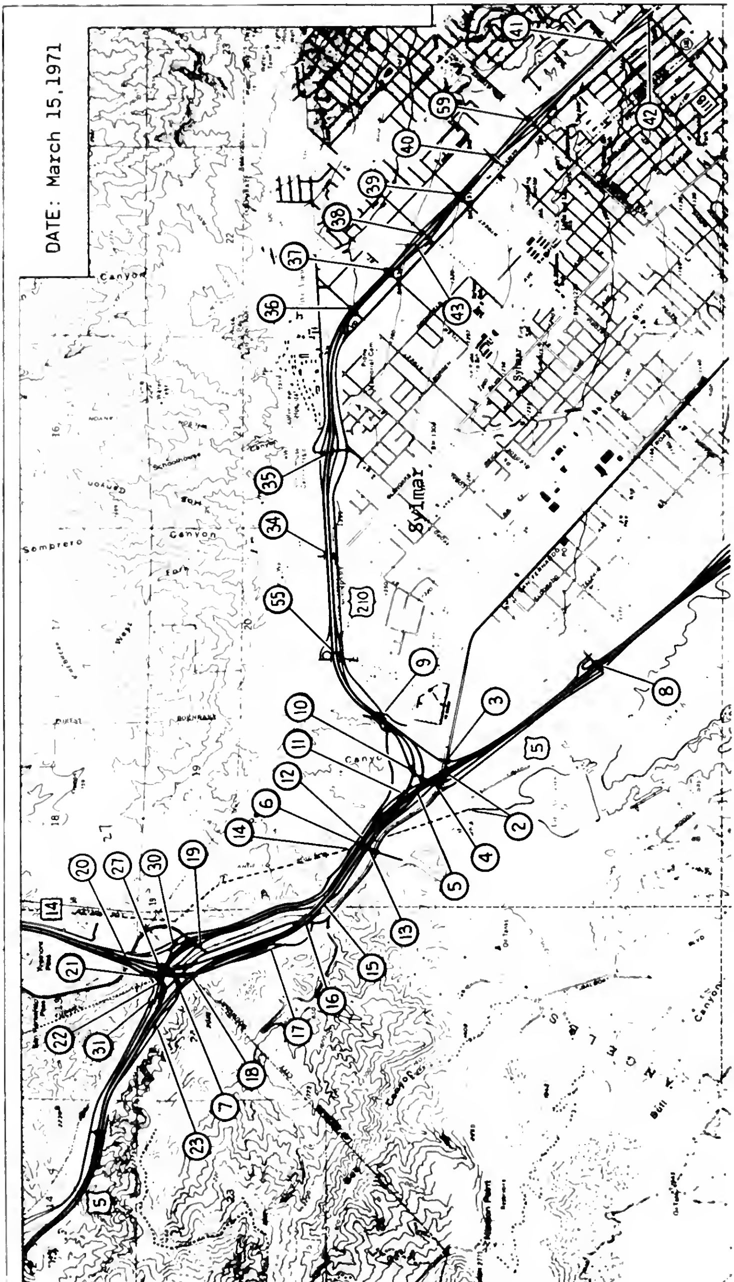


Figure 1. Location of bridges and overcrossings.

Photo 2. Damaged San Fernando Road overhead [2].

Photo 3. Damaged San Fernando Road overhead [2].

Photo 4. Southern portion of the San Fernando Road overhead [2].

Photo 5. Shear failure in column of San Fernando Road overhead [2].

Photo 6. Flexural damage in column of San Fernando Road overhead [2].

stressed concrete structures to the north along the Golden State Freeway. It is significant to note the very narrow ledges which provided bearing-support surfaces for the simple span. The advisability of using such narrow support surfaces in seismic areas should be seriously questioned.

A close-up view of the reinforced concrete bridge system to the left (south) of the railroad is shown again in photo 4. Here, many of the stiffer columns failed by shearing as shown in photo 5, while the more flexible columns sustained flexural damage at their tops as shown in photo 6.

Photo 7 shows a close-up view of similar flexural damage in another nearby column in the same structure. In the column shown in photos 5 to 7, the main reinforcing bars on both sides have been buckled by the flexural compressive forces. Once the concrete cover spalls off the bars, the ties are inadequate to provide the needed lateral constraint to the main reinforcing bars and to provide containment for the concrete. Such damage reduces the flexural energy-absorption capacity of these columns.

An inspection of the bearing and rocker supports of this same bridge reveals that there was large relative displacement of the box girders and their abutment supports. For example, photo 8 shows how one end of a box girder deck moved to the left on its bearing support approximately 1 foot with respect to the abutment.

If one observed these same bridge structures from the top rather than the bottom, he could easily see the large settlment caused by vibration-induced compaction of the soil fills leading up to the bridge abutments. Photo 9 shows the large vertical offset of one of the south abutments.

The highest overcrossing at the Golden State Freeway and Foothill Freeway interchange, which was designed to carry south-bound traffic entering the Golden State Freeway from Foothill Freeway, was damaged in this manner:

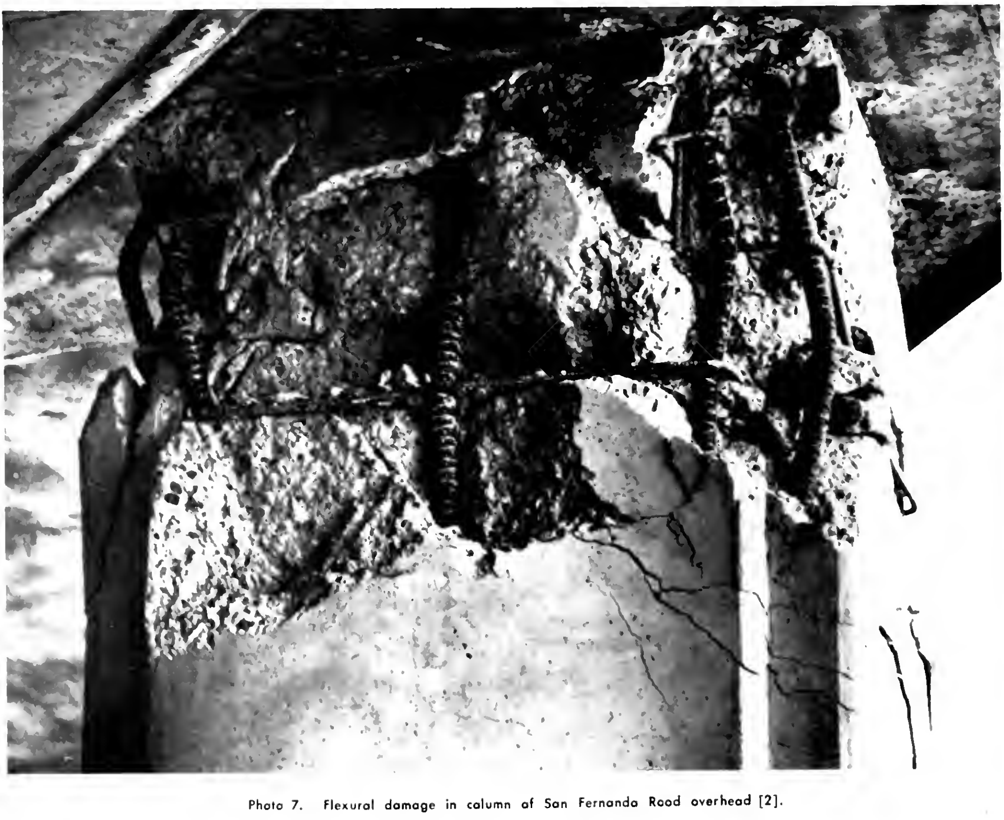


Photo 7. Flexural damage in column of San Fernando Road overhead [2].

Photo 8. View showing horizontal displacement of bridge deck on its support, San Fernando Road overhead [2].

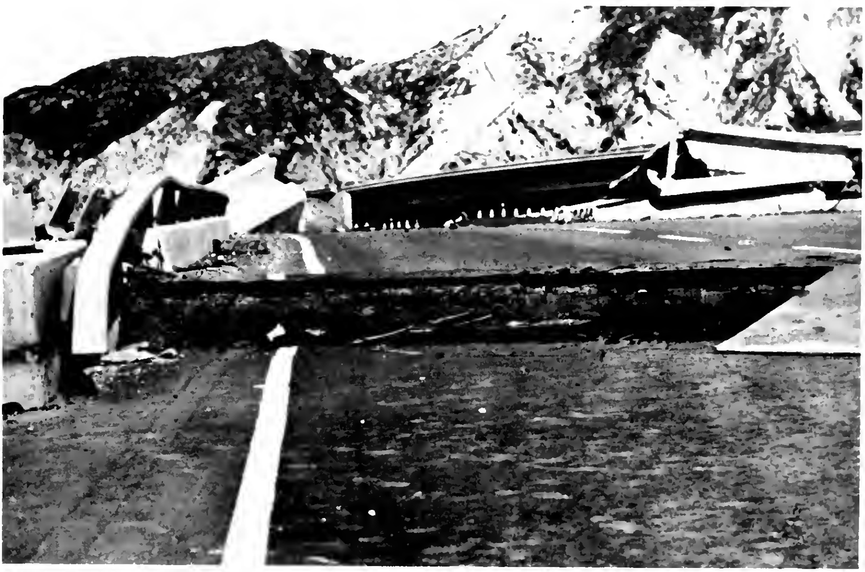


Photo 9. Settlement of backfill at the San Fernando Road overhead [2].

Starting at the south abutment of this overcrossing, as shown in photo 10, the first span of the box girder deck fell on to the side slope. Shown in the foreground of this same figure is the San Fernando Road overhead with its missing span along the Southern Pacific Railroad.

Photo 10. Damaged overcrossing at the Golden State Freeway and Foothill Freeway interchange [4].

The box girder deck of this 770-foot-long overcrossing was supported on six central piers in addition to the end abutments. The two central piers at the south end of the overcrossing were supported on spread footings which were in turn supported on driven concrete piles. Each of the four central piers located at the north end of the overcrossing were supported directly on a single round pile cast directly in a 6-foot-diameter drilled hole. The box girder deck had one expansion joint near mid-crossing in addition to those at the abutments.

Farther north along this same overcrossing, one could observe sections of the collapsed structure in their fallen positions as shown in photo 11. Note that this portion of the overcrossing fell in a westerly direction.

Photo 11. Damaged overcrossing at the Golden State Freeway and Foothill Freeway interchange [4].

Considering the location and orientation of abutments and the expansion joint and the general curvature of the deck as seen in a plan view, it is quite apparent that the deck was highly constrained against large displacement in all directions except the west. Therefore, it is easily understood why the structure collapsed in a westerly direction.

Photo 12 shows the last deck span where it crashed through an overcrossing [5] of the Golden State Freeway which directs traffic coming from the north along the Golden State Freeway onto Foothill Freeway going east.

A close look at the columns of this overcrossing indicates that they generally failed at the bottom because of the superposition of high-flexure forces onto the axial forces. The column shown in photo 13 also experienced flexural cracking at intermediate points where it crashed through the San Fernando Road overcrossing. Such cracks would be expected under such severe impact.

Of much greater significance, however, are the characteristics of failure which were observed at the bases of these columns. Photo 14 shows failure characteristics typical of the columns supported on the 6-foot-diameter cast-in-drilled-hole piles. It is quite apparent that the anchorage of the main reinforcing bars (no. 18 bars) where they extended into the supporting pile was inadequate. Bond failure along the main reinforcing bars was quite evident at these locations.

Photo 12. Damaged overcrossing at the Golden State Freeway and Foothill Freeway interchange [4].

Photo 15 shows the base of one of the two columns that were supporred on spread footings. The main reinforcing bars entered the footing and were bent outward to provide added anchorage. It is quite apparent that the relatively small ties (no. 4 bars) could not possibly have provided the required containment of main reinforcing bars and the enclosed concrete. Lateral forces developed in the main reinforcing bars caused spalling of the concrete cover, thus causing complete loss of bond with the concrete.

Of the two possible causes of collapse, the large vibratory motion induced in the super-structure by the high intensity vertical and horizontal ground acceleration and the ground displacement between abutment and column supports, the authors think that the vibratory motion was the major cause of the collapse of this structure.

Motion and displacement can, of course, combine to produce movement at abutments and expansion joints. In this case, the relative displacement was cer-

Photo 13. Column of overcrossing at the Golden State Freeway and Foothill Freeway interchange [4].

Photo 14. Failure at base of column supported on a single 6-foot-diameter cast-in-drilled-hole pile, Golden State Freeway and Foothill Freeway interchange [4].

Photo 15. Failure at base of column supported on spread footing, Golden State Freeway and Foothill Freeway interchange [4].

tainly sufficiently large to cause the deck spans to drop off their supports, thus initiating complete collapse of the structure.

Golden State Freeway and State Highway 14 Interchange. The location of the Golden State Freeway and State Highway 14 interchange is shown in the upper left of the map (figure 1).

Several of the overcrossings in this interchange were still under construction at the time of the earthquake, as seen in photo 16. In the foreground of this northerly view, one can see a row of newly constructed columns for an overcrossing. Immediately behind these columns, there is steel formwork supporting a newly constructed box girder deck of another overcrossing.

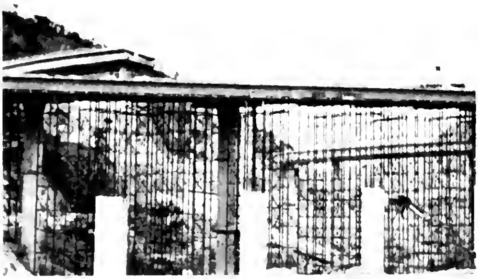


Photo 16. Collapsed overcrossing at the Golden State Freeway and State Highway 14 interchange [7].

Behind the second overcrossing, the highest overcrossing [7] in the interchange can be seen, terminating at one of its expansion joints. From this point on to the right (east), a 354-foot-long section of the overcrossing collapsed during the earthquake. This long, prestressed-concrete section of bridge deck was supported at each end on bearing supports at expansion joints and by a single central column standing approximately 160 feet high. This column can be seen lying in its fallen position on the side hill directly behind the steel formwork shown in photo 16.

The initial cause of collapse of this structure appears to have been the large relative deck displacement of the west expansion joint which allowed the box girder to fall off its bearing supports. The falling cantilevered portion of the deck span pulled the deck system to the west, permitting the east end of the span also to fall off its supports. Both cantilevered portions of the deck span broke off at the top of the central column allowing them to fall almost directly down from their original positions. The central column fell to the west, (photo 17), landing nearly on top of the west portion of the deck span. The top of the central column landed directly on a new truck crane, which was totally destroyed (photo 18).

The eastern portion of the deck slid down the central column as indicated by the dark abrasive markings in photo 17. These markings can also be seen in photo 19, which gives a view of the central column from its top toward bottom.

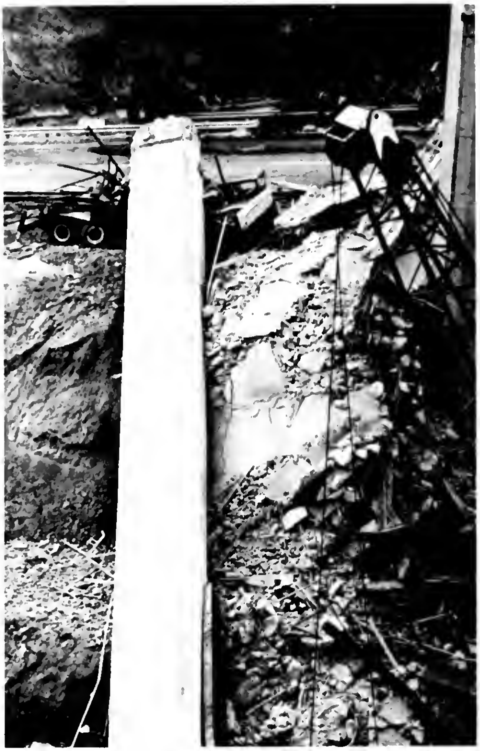


Photo 17. Collapsed span of overcrossing at the Golden State Freeway and State Highway 14 interchange [7].

Photo 18. Crane truck crushed by column, Golden State Freeway and State Highway 14 interchange [7].

Photo 19. Collapsed column of overcrossing at the Golden State Freeway and State Highway 14 interchange [7].

There was settlement of the fill leading up to the abutments of this overcrossing, as shown in photo 20; in addition the timber falsework was surprisingly stable, as shown in photo 21.

Foothill Boulevard Undercrossing at Foothill Freeway. The location of the Foothill Boulevard undercrossing at its intersection with the Foothill Freeway can be seen in figure 1 [9]. Two similar reinforced-concrete, box-girder bridges carry the Foothill Freeway traffic over Foothill Boulevard at this point. These two parallel bridges are shown from below in photo 22, as viewed from Foothill Boulevard toward the west.

The central-span columns of the east bridge sustained heavy shear damage, followed by vertical crushing of the broken concrete causing the main reinforcing bars to buckle outwards. Clearly, the ties (no. 4 bars) provided were inadequate to contain the concrete and provide stability for the main reinforcing steel. The progressively heavier damage observed from the innermost column towards the outermost column would suggest that significant torsional displacement was produced by the earthquake.

Roxford Street Undercrossing at Foothill Freeway. The Roxford Street bridge [35] was a simple-span, prestressed-concrete bridge. No damage to the deck and abutments was observed at this undercrossing.

Photo 20. Settlement of backfill at abutment of overcrossing at the Golden State Freeway and State Highway 14 interchange [7].

Photo 21. Timber falsework at the Golden State Freeway and State Highway 14 interchange.

Photo 23. Damaged wing wall of abutment, Roxford Street undercrossing at Foothill Freeway [35].

Photo 22. Foothill Boulevard undercrossing at Foothill Freeway. View west [9].

Photo 24. Differential settlement of bockfill ot abutment, Roxford Street undercrossing ot Foothill Freewoy [35].

Photo 25. Buckled ospholt pavement caused by large compressive ground deformations.

Photo 26. View showing crushed rock forced out of weep hole. Bledsol Street undercrossing ot Foothill Freewoy [36].

However, one wing-wall had been totally broken away from its abutment, as shown in photo 23, and recent excavations have revealed heavy damage to the piles supporting the abutments. Damage such as this indicates that very high pressure was applied to the abutments during the earthquake.

Ground vibration at this overcrossing caused compaction of all fill placed around the abutments, producing further damage due to differential settlement. Photo 24 shows the amount of differential settlement next to the abutments at one end of this bridge. The tire skid marks on the pavement are a vivid reminder of the hazard to moving vehicles caused by such settlement.

Polk Street Undercrossing at Foothill Freeway. The damage observed at the Polk Street undercrossing [38] at Foothill Freeway was similar to that at the Roxford Street undercrossing; i.e., damage caused by backfill settlement near the abutments and damage to the wing-wall. Large compressive ground deformation caused the asphalt pavement to buckle upwards in one location near this undercrossing, as shown in photo 25.

Hubbard Street Undercrossing at Foothill Freeway. Although the Hubbard Street undercrossing

Photo 27. View of permanent support displacement, Tyler Street pedestrian overcrossinig at Foothill Freeway [37].

Photo 28. Base of column, Tyler Street pedestrian overcrossing at Foothill Freeway [37].

showed no structural damage, settlement of the fill caused differential vertical displacement at the abutments. Near this bridge, excessive compressive ground deformation caused upward buckling of the asphalt pavement similar to that in photo 25.

Bledsol Street Undercrossing at Foothill Freeway. Besides settlement of fill, longitudinal oscillation of the bridge at the Bledsol Street undercrossing [36] apparently was strong enough to force crushed rock out of a weep hole, as shown in photo 26. There was no evidence that water had forced the rock out of the hole or out of other holes where the same thing occurred.

Tyler Street Pedestrian Overcrossing at Foothill Freeway. The Tyler Street pedestrian overcrossing [37] at Foothill Freeway was fairly heavily damaged, mainly along its longitudinal axis, because of vibration. The amount of permanent longitudinal displacement could be most readily seen at the north support as shown in photo 27. This deformation caused serious flexural damage at the tops of the columns. Although only minor damage could be observed at the bases of these columns (photo 28), considerable flexural damage should be expected at the level of the footings.

Via Princessa Undercrossing on State Highway 14. This simple-span bridge [20] has a bearing support at one abutment and a pinned support at the other. The longitudinal forces developed in the bridge deck during the earthquake were sufficient to cause severe flexure-cracking in the diaphragm abutment at the pinned end.

Santa Clara Overhead Crossing on State Highway 14. Considerable pounding damage along the expansion joints of the Santa Clara overhead crossing on State Highway 14 was observed, (photo 29), as well as a buckled flexible splice (photo 30) in a steel conduit to be placed within the concrete bridge curbing which had not yet been poured.

Shear damage and design specifications. The maximum base shears, occurring in linear elastic structures responding as single-degree-of-freedom systems to horizontal ground motions, can be evaluated using response spectrum curves. For example, extrapolating G. Housner's design-response spectrum curves (1970, p. 94) to a period of vibration T equal to 4.9 seconds and using a damping coefficient of 5 percent of critical, one obtains a base shear coefficient approximately equal to 0.085 g for the El Centro, California, earthquake of 1940. A period of 4.9 seconds is assumed in this example, as it corresponds to the transverse period of vibration given by the code formula $T = 0.32 \sqrt{D/P}$, where D = dead load reaction of structural and P = force required for 1 inch horizontal deflection of structure (California Division of Highways, 1968, pp. 2–24) for the high overcrossing which collapsed at the Golden State Freeway-State Highway 14 interchange [7].

It is extremely significant that this base shear coefficient (0.085 g) is much greater than the design base shear coefficient (C) of 0.030 g given by the empirical code formula $C = 0.05/\sqrt[3]{T}$. This simple comparison alone indicates that the present code seismic forces are too low for design purposes.

Photo 29. Pounding damage at expansion joint, Santa Clara overhead crossing on State Highway 14.

Photo 30. Buckled flexible splice in steel conduit, Santa Clara overhead crossing on State Highway 14.

CONCLUSIONS AND RECOMMENDATIONS

Ground Motion

While it is difficult to assess quantitatively the intensities at the location of the damaged highway structures, it is reasonable to expect that similar intensities will occur during future earthquakes of moderate to large magnitude. Full consideration should, therefore, be given to this possibility in the design of all highway structures located in seismically active regions.

Seismic Forces

The use of the formula $C = 0.05/\sqrt[3]{T}$ in the design of highway bridge structures should be seriously questioned and reconsidered for several reasons:

(1) It was originally developed for use in the design of buildings, which are not equivalent to bridges in their earthquake behavior. Specifically, it is known that nonstructural components, such as interior walls and exterior cladding, contribute significantly to the earthquake response of buildings.

(2) The seismic coefficient prescribed for the design of buildings does not represent the full force expected by a major earthquake; it is expected that inelastic deformation will result from a major earthquake, and the designer is expected to insure adequate ductile deformability of the structure.

(3) The formula for evaluation of the period of vibration of the structure is grossly oversimplified. It must be recognized in evaluating the vibration period that the bridge deck will be subject, in many cases, to lateral flexure during earthquakes.

Causes of Collapse

Two possible causes of collapse of the high overcrossings [3, 4, 7] are: (1) large vibratory motion induced in super-structures by high-intensity vertical and horizontal ground acceleration and (2) relative ground displacement between the abutment and column supports. It is the opinion of the authors that vibratory motion was the major cause of the collapse of these structures. We found no evidence that relative displacement was a contributing factor.

Design Considerations

1. **Expansion Joints**—Collapse of the high overcrossings was initiated by bridge spans falling off their supports at abutments and expansion joints due to excessive displacement of the spans relative to their supports. This type of behavior should be carefully examined and corrective measures should be taken as soon as possible. Full consideration should be given to eliminating expansion joints wherever feasible, to widening bearing supports, and to providing more effective ties across expansion joints.

2. **Columns**—Failure in the central portion of the shorter stiff columns was caused by transverse shear forces, while end failure in the larger, more flexible columns was caused by flexural forces. In each case, there was a noticeable lack of transverse ties. Clearly, the design details of columns should be carefully examined, particularly with regard to size and placement of reinforcing bars and ties, and corrective measures should be taken to improve their performance under ultimate loading conditions involving reverse deformation cycles such as occur during major earthquakes.

3. **Column Caps**—There appears to be a serious lack of reinforcing bars tying column caps onto their respective box girder bridge decks. Corrective measures should be taken to improve this design detail.

4. **Column Foundations**—Failure at the base of columns for both types of support; i.e., single cast-in-place pile and spread footings with driven piles showed inadequate anchorage of the main reinforcing bars. Corrective measures should be taken so that sufficient anchorage is provided to develop the full strength of the main reinforcing bars.

5. **Abutments and Wing Walls**—Failure in abutments and wing walls were caused by large dynamic forces transmitted by backfill earth pressure and by seismic forces developed in the bridge decks. The design details of these structures should be re-examined and appropriate corrective measures should be taken to improve their performance characteristics.

Design Philosophy

The present elastic design philosophy using equivalent static loading to represent seismic effects should be reviewed and appropriate code changes should be made to improve: (1) response to the dynamic character and intensity of seismic loading; (2) structural characteristics under ultimate loading conditions, particularly strength and ductility; and (3) behavior when deformed beyond the elastic limit.

Needed Research

The damage to bridge structures during the San Fernando earthquake point up the urgent need for both theoretical and experimental research related directly to seismic effects on bridge structures.

It is recommended that theoretical studies, consisting mainly of dynamic analyses of several of the high overcrossings which failed, be initiated as soon as possible and that experimental investigations be undertaken as soon as meaningful programs can be defined. These experimental studies should include investigations of bond and confinement in typical large-size pier sections, as well as of the dynamic behavior of typical bridge systems.

CHAPTER 29

Effects of the San Fernando Earthquake on the Van Norman Reservoir Complex [1]

by Clifford J. Cortright [2]

The purpose of this report is twofold: (1) to document in preliminary form the effects of the San Fernando earthquake of February 9, 1971, on the Van Norman Reservoir Complex, particularly on the Upper and Lower San Fernando Dams which were severely affected; and (2) to indicate the nature of the investigations being conducted, together with a preliminary analysis of the mechanics of the slide which took place at Lower San Fernando Dam.

Immediately following the San Fernando earthquake of February 9, 1971, an investigation of the effects of the earthquake on the Van Norman Reservoir Complex was initiated by the State Division of Safety of Dams. Such an investigation of Lower San Fernando Dam is extremely important, whether or not the dam is reconstructed. This dam is one of the more than 30 hydraulic fill dams within jurisdiction of the State with respect to safety. There is an urgent need to know what happened, why it happened, and what needs to be done to assure that under comparable circumstances it would not happen to any other of these dams.

As someone has said, with undisguised naivete, each earthquake is a surprise. We in California have long since learned to expect earthquakes from time to time—we *know* we are going to have them—and for years we have designed structures to be earthquake-resistant. Yet, when we have a quake, we *are* surprised—surprised by its location, by its timing, by its effect on people, by its effect on structures. Certainly, there is nothing more unsettling, more fear-evoking, than a rupturing and strong shaking of the earth.

The San Fernando earthquake of February 9, 1971, was no less a surprise than its major predecessors. For one thing, its location was completely unexpected. For another, that the movement occurred along a thrust fault is in itself unusual. Then, too, although registering a magnitude of only 6½ on the Richter scale, it developed the largest ground accelerations ever recorded. And, for an earthquake of such relatively moderate magnitude, its effect on structures was phenomenal, despite an extremely short duration of strong shaking of only 12 or 13 seconds.

Damage resulted from fractures, lurching, shaking, and differential movement. Actual ruptures of the earth, of streets, of utilities, of buildings, were common along the fault trace in San Fernando and Sylmar and elsewhere (see figure 1). A major water supply tunnel, under construction, had differential vertical movement exceeding 6 feet. Damage from shaking predominated, however, to hospitals, schools, and other major buildings; to highway interchanges; to power switchyards and water treatment facilities; and to the two major dams of the Van Norman Reservoir Complex—Upper and Lower San Fernando Dams.

This report has to do primarily with these two dams. Why did they respond as they did? What were the earthquake forces involved? Why was the recently constructed rolled fill embankment of the Lower Van Norman Bypass Dam apparently unaffected by the earthquake, with so much damage elsewhere in the vicinity? These are questions which need to be resolved, and this interim report will set the stage toward such resolution. These questions are pertinent, not only to the Van Norman Reservoir Complex and to repair or reconstruction of the dams involved, but to all embankment dams which have similar characteristics.

Both Upper and Lower San Fernando Dams are hydraulic fills. There are 30 other hydraulic fill dams within jurisdiction of the State for safety. Will these dams react similarly if subjected to a similar earthquake? Or how about an even larger earthquake, a great earthquake like San Francisco in 1906 or Fort Tejon in 1857? Are all hydraulic fill dams suspect? Many dams throughout the United States are hydraulic fills, and some are very large. For example, the Fort Peck Dam on the Missouri River in Montana is to date the largest earthfill ever constructed in the western hemisphere; it, too, is a hydraulic fill. The Kingsley Dam on the North Platte River in Nebraska is a very large hydraulic fill. The Miami Conservancy District in Ohio built several such dams before 1920. Cobble Mountain Dam and Quabbin Dike in Massachusetts are

[1] Manuscript submitted for publication October 5, 1971. The field investigation was conducted and the report on the history and effects of the earthquake was prepared by Roger E. Stephenson, Alberico A. Coluzzi, and Warren D. Pedersen of the State Division of Safety of Dams. The section on the Lower San Fernando Dam slide has been abridged from a preliminary report prepared by H. Bolton Seed, K. L. Lee, and I. M. Idriss of the Department of Civil Engineering of the University of California, Berkeley.

[2] Division Engineer, Division of Safety of Dams, California Department of Water Resources.

Table 1. Selected acceleration data, San Fernando earthquake of February 9, 1971

No.	Location*	Seismic instrument type and number	Acceleration data: Horizontal Alignment	Horizontal Maximum % g	Horizontal Alignment	Horizontal Maximum % g	Vertical Maximum % g	Approximate distance to epicenter (miles)
1	Santa Felicia Dam (outlet works)	AR 240 S/N 242	S82°W	.237	S8°E	.230	.092	25
2	Glendale—633 E. Broadway	AR 240 S/N 216	S70°E	.275	S20°W	.233	.142	22
3	Los Angeles—8244 Orion	AR 240 S/N 190	N-S	.276	E-W	.145	.171	17
4	Castaic—Old Ridge Route	AR 240 S/N 124	N69°W	.388	N21°E	.316	.178	18
5	Pasadena—Milliken Library at Cal Tech.	RFT 250 S/N 198	N-S	.216	E-W	.184	.116	24
6	Pacoima Dam—Left Abutment	AR 240 S/N 179	S74°W	1.01	S16°E	.61	.7	8
7	Los Angeles—3838 Lankershim	RFT 250 S/N 155	N-S	.175	E-W	.127	.087	21
8	Los Angeles—15107 Vanowen	RFT 250 S/N 267	N-S	.120	E-W	.107	.116	19
9	Los Angeles—15250 Ventura	SMA-1 S/N 185	N11°E	.227	N79°W	.140	.10	22
10	Arcadia—Santa Anita Reservoir	AR 240 S/N 183	N3°E	.179	N87°W	.236	.068	25
11	Alhambra—900 S. Fremont	SMA-1 S/N 165	N-S	.108	E-W	.127	.093	28
12	Beverly Hills—9100 Wilshire	MO-2 S/N 148	N-S	.123	E-W	.161	.037	26
13	Hollywood—1760 N. Orchid	MO-2 S/N 152	N-S	.163	E-W	.131	.072	24
14	Los Angeles—1177 Beverly Drive	MO-2 S/N 170	N31°W	.123	N59°E	.114	.067	25
15	Los Angeles—234 Figueroa	MO-2	S53°E	.173	N37°E	.197	.057	27
16	Palmdale—Fire Station	RFT-250 S/N 189	S60°E	.110	S30°W	.131	.084	15
17	Los Angeles—Griffith Observatory	RFT 250 S/N 158	N-S	.184	E-W	.163	.121	23

* See figure 1 for location of instruments. Seismographs in buildings are at ground level.

hydraulic fill dams. Several of these dams are in the range of 150 to 250 feet in height. With the advent of the wheel scraper and an effective tamping roller in the early 1930s, and later the high speed, large-capacity loading and hauling equipment and even better rollers, hydraulic fill dams have become economically obsolete in the United States. However, between about 1910 and 1941, the hydraulic fill was a most popular method of constructing earth dams because of its economy in terms of construction methods then available. Therefore, the investigations conducted at the Van Norman Reservoir Complex are of significant importance to the entire dam-building profession, not only here in California, but throughout the United States and possibly the world.

HISTORY AND DESCRIPTION OF THE VAN NORMAN RESERVOIR COMPLEX

Los Angeles Aqueduct

Los Angeles, established by the Spanish Crown in 1781, had grown to a city of a half million by 1913. By this date the local water resources had been well developed; and, in order to ensure an adequate water supply and to prepare for the potential growth of the area, an additional source of water was required. The search for a dependable water supply was started in early 1900; and, after the consideration of various alternatives, the decision was made to bring water from the Owens River by what was to be known as the Los Angeles Aqueduct. The work on the first phase of the aqueduct was started in late 1907 and completed in 1913 at a cost of $23 million. This phase began with the headworks diverting the Owens River into the aqueduct near the town of Aberdeen, 30 miles south of Bishop, in Owens Valley, Inyo County.

By a series of canals, tunnels, siphons, and reservoirs, water was conveyed southward along the east side of the Sierra Nevada, across the Mojave Desert (Antelope Valley), and initially into San Fernando No. 2 Reservoir, now known as Lower Van Norman Reservoir, and later, in 1922, into San Fernando No. 1 Reservoir, now known as Upper Van Norman Reservoir. The original design of the aqueduct provided for a mean annual flow of 400 cubic feet per second of water at the terminus. However, historically the average annual flow has been on the order of 440 cfs, or a total annual quantity of about 320,000 acre-feet. In 1932, Tinemaha Reservoir was constructed on the Owens River near Independence, and in 1940 the water tributary to the Mono Basin was brought into the system with the completion of the Mono Craters Tunnel and Crowley Lake.

In 1970 the second Los Angeles Aqueduct was completed, and an additional flow of approximately 285 cfs was routed into the Van Norman Reservoir Complex. The capacity of this second aqueduct from the Bouquet Reservoir pipeline to the Van Norman Reservoirs is approximately 350 cfs, thus allowing Bouquet Reservoir to be used as both a storage and a regulating reservoir.

The importance of the Los Angeles Aqueducts is readily apparent when it is noted that, prior to the February 9 earthquake, it was estimated that these supply lines would carry about 80 percent of the City's supply in the year 1970–71.

Lower San Fernando Dam

In order to provide for terminal storage at a location close to the city and at an elevation that would provide for efficient delivery of water to the distribution system, the construction of Lower San Fernando

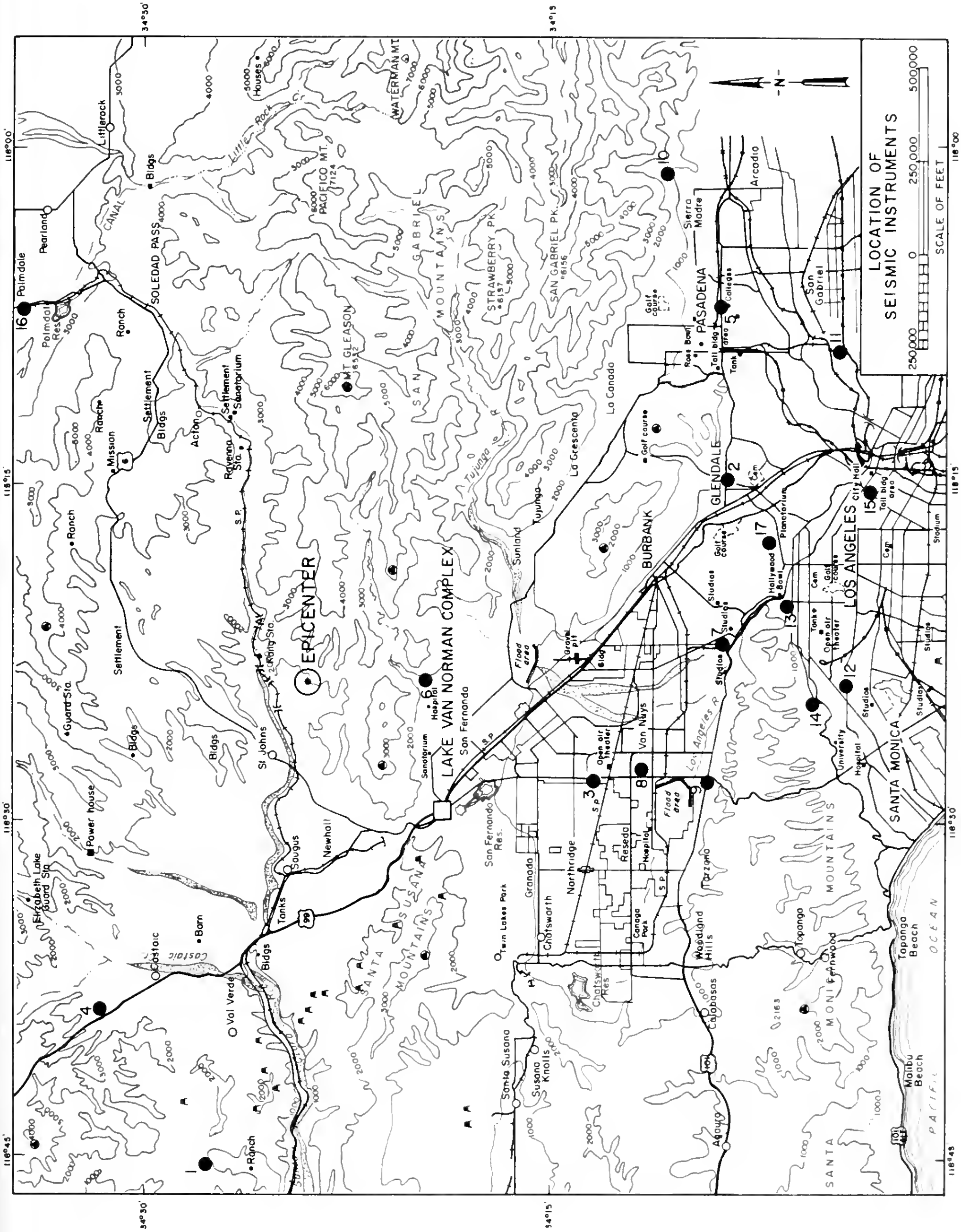


Figure 1. Location of seismic instruments for selected acceleration data.

Dam (Lower Van Norman Reservoir) was started in 1912. Although at that time the economy of the site was questioned because of the large-size dam required for the amount of storage to be gained, it was finally given favorable consideration because of the suitability of construction material close to the dam for hydraulic fill construction.

Between 1912 and 1915, the embankment was constructed to about Elevation 1080 at the axis and 1090 at the upstream and downstream edges (streambed at axis was approximately at Elevation 995) using material hydraulicked from the floor of the reservoir.

The dam is founded on a dense clay alluvium with lenses of sand overlying an impervious complex of shales and sandstones to a reported depth of about 35 feet. There are reported to be three cutoff trenches through this alluvium which are backfilled with hydraulicked material.

The dam was essentially a hydraulic fill embankment capped by a potpourri of wagon-dumped and rolled fill founded on alluvium with three cutoff trenches to bedrock; it had an upstream slope of 2½:1; downstream slopes of 2½:1 and 4½:1; with a 20-foot berm at Elevation 1096, a height of 142 feet, crest width of 20 feet, and a length of 2180 feet. It was faced upstream with lightly reinforced concrete and had a 3-foot-high concrete parapet wall at the upstream edge of the crest. Altogether, about 3.3 million cubic yards of embankment were used in construction to impound 25,500 acre-feet of water.

In 1967 on the recommendation of the City's consultants, concurred in by the State Division of Safety of Dams, the reservoir was being operated at a maximum water surface elevation of 1125 or 9.65 feet below the spillway crest elevation. This additional freeboard was maintained because of uncertainty with respect to construction methods, the history of the dam, and the results of the City's slope-stability analysis performed in 1967. As part of the City's long-range facility improvement program, this dam was scheduled to be strengthened or reconstructed about 1973 or 1974. The Lower Van Norman Bypass Reservoir had been completed and placed into service in July 1970 in preparation for taking the Lower Van Norman Reservoir out of service for alteration.

Surveillance of the Lower San Fernando Dam included measuring horizontal movement and settlement of the dam through monuments located initially on the parapet wall and later in the embankment on the dam crest. Observation wells were located on the upstream and downstream slopes of the dam to measure the phraetic line within the embankment at various locations. Seepage collected by drains in the foundation of the dam was routinely measured and recorded. A Wilmot seismoscope and a Teledyne peak-recording accelerograph were located on the crest near the center of the dam, and another Wilmot seismoscope was located on the east (left) abutment. Three tiltmeters were located at the crest, on the Elevation 1096 berm, and at the toe of the dam. All surveillance data were reviewed periodically by the Los Angeles Department of Water and Power and the State Division of Safety of Dams.

Lower San Fernando Dam, Geology and Foundation Conditions

The dam embankment in the channel section and the lowermost portions of the abutments rest on Holocene alluvium which, according to City records, consists of dense clay with lenses of sand and gravel. This alluvium attains a maximum thickness of approximately 35 feet beneath the dam. Three earth-filled cutoff trenches constructed prior to the placement of the hydraulic fill intercept this alluvial section and extend into the underlying sedimentary bedrock.

Three marine sedimentary formations comprise

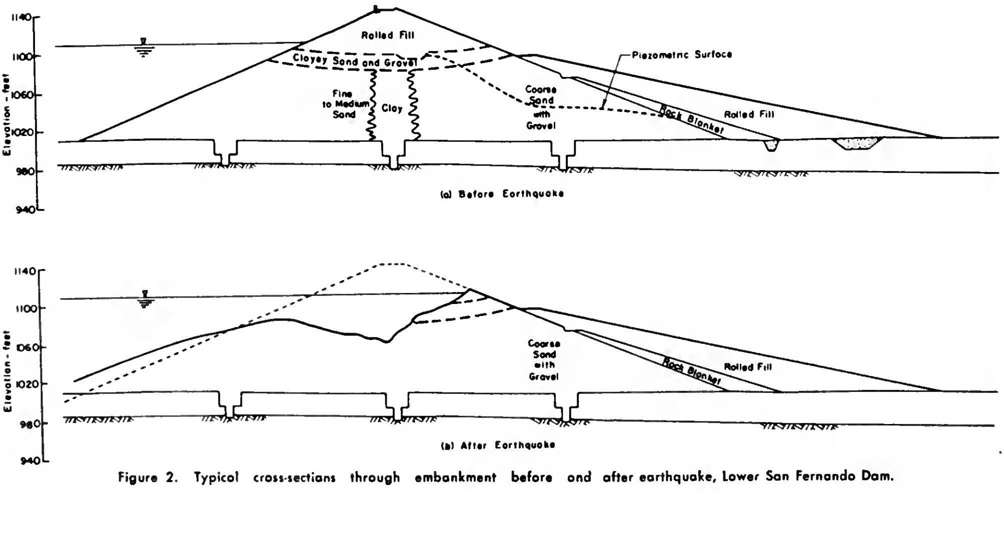


Figure 2. Typical cross-sections through embankment before and after earthquake, Lower San Fernando Dam.

Photo 1. Aerial photo of Lower San Fernando Dam after earthquake.

the bedrock that forms the abutments and the foundation beneath the alluvium and the hydraulic and rolled fills. These formations from oldest to youngest and from east to west are the Modelo of late Miocene age, the Repetto of early Pliocene, and the lower member of the Pico of middle Pliocene age.

The Modelo Formation underlies the east, always called the left, abutment. It extends under the dam a short distance toward the west, dipping about 40 degrees southwesterly beneath the dam. It consists of gray to brown, thinly stratified diatomaceous shale, siliceous shale, and siltstone. The upper 30 to 50 feet of the Modelo Formation are weathered to varying degrees and contain numerous gypsum-filled seams along joints, fractures, and bedding planes. It is on this weathered and fractured phase that the left end of the dam rests. Dissolving of this gypsum by reservoir waters through the years is believed to have been a cause of the excessive seepage through the left abutment which existed prior to extensive grouting of the abutment in 1964.

The next younger formation, the Repetto Formation, overlies the Modelo Formation and likewise dips westerly toward the right abutment. It consists of clay, siltstone, and diatomaceous shale. Its subsurface extent as measured on the dam axis is approximately 800 feet from Station 3+00 to Station 11+00. The nature of the contact here between the Modelo and the Repetto Formations is not known with any degree of certainty.

The lower member of the Pico Formation is in normal depositional contact with the underlying Repetto Formation and extends westerly from about Station 11+00 to beyond the end of the dam and forms the entire right abutment. The Pico Formation here at the dam consists largely of massive, friable, coarse gray-white sandstone with lesser amounts of finer-grained sandstone. The Pico Formation, as well as the underlying Repetto Formation, dips from 30 to 50 degrees northwesterly.

The most significant structural feature at the dam is the Mission Hills anticline, the north limb of which forms the left abutment. The anticline plunges from 30 to 45 degrees to the west. The highly fractured nature of the Modelo Formation on the left abutment may in part be attributable to the folding of the beds along the anticlinal axis.

Upper San Fernando Dam

The Upper San Fernando Dam, a semihydraulic and dry-fill embankment, was constructed to provide flexibility of operation and supplementary storage at the terminus of the Los Angeles Aqueduct. The semihydraulic fill portion was constructed to about Elevation 1200 in 1921 by using about 500,000 cubic yards of material obtained from the reservoir area of the valley floor. Although it was originally planned to be constructed to Elevation 1238 in 1922, the dam was instead raised to Elevation 1218 by placing some 50,000 cubic yards of compacted dry fill on the upstream side. The dry-fill material was obtained from side-hill borrow, spread in thin layers, sprinkled and wagon-rolled. The completed section of the dam has a 2.5:1 concrete paved upstream slope, a crest 20 feet wide, and a downstream slope of 2.5:1 with a 100-foot berm at Elevation 1200. Originally, the reservoir capacity was 1977 acre-feet, but the storage capacity was reduced to 1848 acre-feet by siltation during the 1938 flood and later by the construction of the dikes along the western side of the reservoir. These dikes provide flood-control protection and divert the local upstream runoff and debris from the reservoir.

The method of construction used material hauled by wagons from the borrow area to the edges of the embankment where it was dumped then dispersed by monitors working from barges floating in the center pool. This was common procedure when water was in short supply and it was necessary to recycle the pool water. The rolled-fill section was probably placed in similar manner to others built at the time. It was common procedure to haul the material from the borrow, deposit on the fill and spread in lifts using teams and Fresno scrapers and, after sprinkling, to provide compaction by routing the haul wagons over the area.

Available cross sections of the dam show a cutoff trench extending to a depth of 4 feet into alluvium for a width of 30 feet. This was probably intended only to cut off rodent holes and vegetation. Recent exploration indicates alluvium has a depth of 50 feet.

An outlet tower stands just upstream of the toe of the embankment at about the midpoint of the dam. The tower is founded on alluvium at about Elevation 1149 and rises about 90 feet to Elevation 1239. It is similar to the towers at the lower reservoir having a constant outside diameter of 20 feet and stepped internal diameters of about 16, 14, 12, and 10 feet. The tower connects to an 8-foot-diameter concrete cast-in-place outlet pipe. This pipe has a 62-inch inside diameter reinforced-concrete steel cylinder pipe with lead-filled joints inserted through it with the annular space between the two filled with concrete for the upstream 160 feet.

In 1968 a second outlet was constructed by concrete encasement of a 99-inch welded steel pipe through the right abutment at an inlet elevation of 1185. In addition to these outlets, it has been standard procedure to operate the reservoir to spill water into the lower reservoir through the overflow spillway at the left of the dam. A bypass of the upper reservoir is available through an open channel which skirts the east side of the reservoir and connects the aqueduct above the reservoir with the spillway chute going into Lower Van Norman Reservoir. As part of the City's over-all facility improvement program, the upper reservoir was scheduled to be used without overflowing the spill-

Photo 2. Slide damage at east end of embankment, Lower San Fernando Dam.

way, together with the newly constructed Lower Van Norman Bypass Reservoir, during the reconstruction of the Lower San Fernando Dam which was scheduled for about 1973 or 1974.

Movement and settlement data are obtained by periodic resurveys of monuments located in the parapet wall and embedded in the embankment at the center of the dam crest. Observation wells have been placed on the downstream slope and berm to determine the elevation of the phreatic line within the embankment. Drains are provided at the abutment contacts and toe of the dam. Flow from these drains is measured regularly. A basin drain was provided to remove any water that accumulates under the dumped backfill in the area below the dam. This drainage system was constructed in 1965. Surveillance measurements are made regularly.

Geologic and foundation conditions at Upper San Fernando Dam are not nearly so well understood as they are at the lower dam. Little or no exploration had been conducted at the upper dam up to the time of the start of the investigation following the February 9 earthquake. Information is now (1971) being obtained by the current drilling and sampling program.

The dam embankment is known to be founded on Holocene alluvium, which recent exploration has shown to be about 50 feet thick. The right abutment consists of beds of the Saugus Formation striking parallel to the axis of the dam and dipping northwesterly approximately 60 degrees. The Saugus Formation probably is of early Pleistocene age and consists of light-colored, well-graded, poorly cemented conglomeratic sandstone and coarse-grained sandstone. Some finer-grained phases are present also. The Saugus Formation is believed to have been deposited as fluviatile and alluvial-fan sediments rather than as marine sediments. The presence of small to moderate amounts of cementing material renders these sediments relatively impervious.

Fanglomerate deposits of the Pacoima Formation of Pleistocene age cover the left abutment. It is suspected, however, that these older alluvial sediments constitute a capping of the abutment and that the excavation for the left end of the dam and for the spillway encountered the underlying beds of the Saugus Formation, similar to those that appear on the right abutment of the dam.

EFFECTS OF THE EARTHQUAKE

The earthquake of February 9, 1971, which centered about 10 miles north of the city of San Fernando at a depth of about 8 miles and registered 6.6 on the Richter scale, caused loss of life and property throughout the north portion of the San Fernando Valley. Energy released by the earthquake subjected the Van Norman Reservoir Complex, 1½ miles west of San Fernando, to severe ground motion. The Lower San Fernando Dam was severely damaged and had to be taken out of service; the Upper San Fernando Dam was impaired and had to be operated at a lowered water surface elevation. The facilities through which water discharges into the Upper Van Norman Reservoir were rendered unusable. The Lower Van Norman Bypass Reservoir Dam showed surface cracks in the asphalt lining; however, no damage to the embankment or structures was detected. Peripheral structures of the complex, that isolate the three storage reservoirs from stormflows, apparently suffered only minor damage.

Lower San Fernando Dam

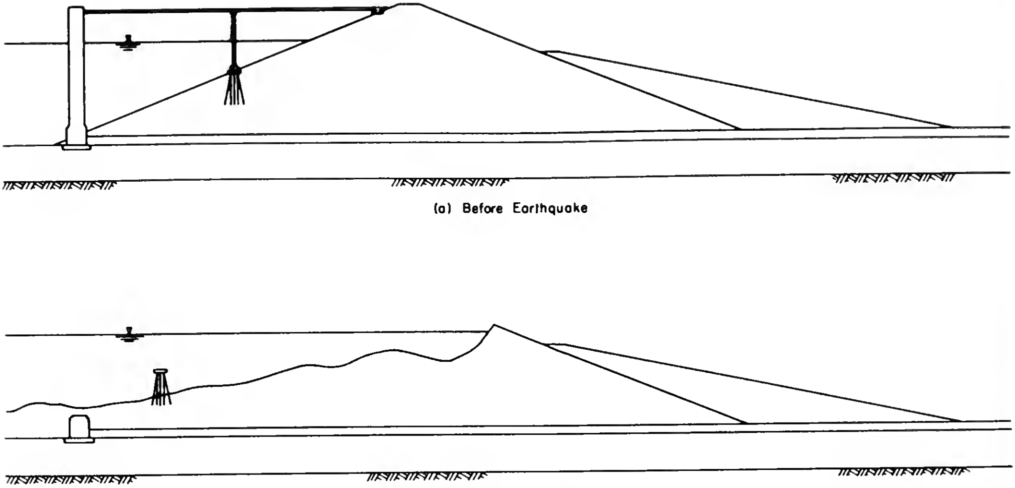
The Lower San Fernando Dam was the worst damaged of all the dams in the complex. The embankment including the parapet wall, the dam crest, most of the upstream slope, and a portion of the downstream slope for a length of about 1800 feet slid into the reservoir. As much as 800,000 cubic yards of dam embankment may have been displaced into the reservoir, resulting in a loss of about 30 feet of dam height.

Shortly after the major damage to the dam had been assessed, several hundred sandbags were filled and stored on the downstream slope above the Elevation 1095 berm. These were made ready for use in the event that aftershocks would bring about a significant decrease in the minimum freeboard remaining. Because of the critically reduced freeboard, the uncertain degree of damage to the Upper San Fernando Dam and the possibility of strong aftershocks, residents in an endangered area below the dam were evacuated.

The east outlet tower was cracked at the base, broken off about 20 feet above the base, and came to rest in an upstream orientation. The sliding earthfill and concrete slope paving covered the remaining upright stem of the tower and blocked the opening to the outlet conduit, temporarily restricting flow through this outlet to approximately 100 cfs. Within a short period, the entrance to the tower stem became sufficiently cleared so that this outlet was quite effective in evacuating the reservoir. The west tower (on the right abutment) did not suffer any noticeable damage and was used to dewater the reservoir to about Elevation 1091, the invert of the lowest operating gate. During erosion and clearing of the debris that had blocked the broken east tower stem, small pieces of concrete, as well as earth, were carried into the outlet line and into the distribution mains.

Since mid-1966, the Lower Van Norman Reservoir had been operated at restricted storage, with maximum operating level not permitted to fill above Elevation 1125, about 10 feet below spillway crest. At the time of the earthquake, the reservoir was storing about 11,000 acre-feet of water compared to its capacity of 20,500 acre-feet. The water surface elevation was about 1109 and 25 feet below the dam spillway, about 35 feet below the dam crest. Inflow to the reservoir was about 475 cfs via the Upper Van Norman Reservoir bypass channel, Upper San Fernando Dam operating spillway, and Lower Van Norman Bypass Reservoir operating spillway. Outflow from the reservoir was about 190 cfs from Tower No. 1 (east), through the 78-inch, reinforced concrete pipe, and about 200 cfs from Tower No. 2 (west) at the right abutment, through the 72-inch welded steel pipe, for a total of about 390 cfs.

As soon as possible following the quake, all the inflow to the reservoir was turned off. As the center tower was cleared through erosion of the debris that



(a) Before Earthquake

(b) After Earthquake

Figure 3. Schematic cross-sections near central intake tower, Lower Von Norman Reservoir.

had slid over it, combined flow through both towers increased to about 650 cfs. Most of the outflow from the towers was taken into the City's delivery system. Some was wasted through three 12-inch blowoff valves discharging into the unpaved channel downstream from the dam and finally into the nearby Bull Creek channel. The Corps of Engineers provided additional evacuation capacity by installing pumps near the shoreline a short distance upstream from the right outlet tower. These pumps, having a combined capacity of about 70 cfs, discharged into the Lower San Fernando spillway chute which also enters Bull Creek channel. During peak evacuation, when all available outlets were being used, a maximum outflow from Lower Van Norman Reservoir of about 700 cfs was attained.

After the reservoir surface had been reduced to a safe level, the flow was reduced and blended with better quality water to improve the overall quality of water delivered into the system. As the reservoir drained to the point where only unsatisfactory water remained, deliveries into the system were curtailed and the remaining water was flushed into Bull Creek.

Surveillance data were taken as quickly as possible following the earthquake, and it was noted that seepage had increased for a short period. Several seepage flows became turbid at first, but all cleared within 36 hours after the 'quake. Observation wells were measured and showed an initial rise in water surface elevation which later returned to normal and decreased with the evacuation of the reservoir. The seismoscope and the accelerograph located on the dam crest opposite the east tower went into the water with the sliding embankment but were recovered intact after the water level had receded.

Upper San Fernando Dam

The 'quake damaged the Upper San Fernando Dam by causing it to move downstream and to slump downhill. The dam crest moved about 5 feet downstream and settled about 3 feet vertically. The upstream concrete slope paving was displaced and damaged, particularly near Elevation 1198, which is coincident with the contact between the "semihydraulic" and wagon-rolled embankment. The reservoir was drawn down quickly to Elevation 1193, then continued in operation to provide aqueduct water into the City's system. The outlet tower remained upright although considerably damaged. The outlet line from the tower was severely affected by the dam's movement and several openings developed.

Shortly after the main shock, it was discovered that very muddy water was issuing from the downstream toe of the dam. This water appeared to be coming from around the outside of the old outlet line, which was in use. After the gates in the outlet tower were closed along with a gate downstream in the outlet line and the pressure removed from this portion of the line between the tower and the closed gate by opening two blowoff valves, the flow at the toe of the dam dropped to an insignificant rate (15 to 20 gpm) and cleared up considerably. These valve operations stopped possible serious erosion of the dam.

The second outlet through the west (right) embankment withstood the 'quake without any visible damage and remained operable. The concrete open channel spillway at the left end of the dam was cracked transversely downstream of the crest and bulged through a portion of the chute section. In

Photo 3. Pile-supported footing for foot bridge to intake tower after slide.

line with the transverse crack was the Upper Van Norman Reservoir bypass channel, which was used to accept flow directly from the aqueduct and bypass the pumping plant and/or the reservoir, with discharge into Lower Van Norman Reservoir. The lining of the bypass channel and entrance into the spillway chute were quite badly damaged.

The water surface elevation at the time of the 'quake was about 1213.2 or about 0.7 foot above the spillway crest. The reservoir was spilling into the Lower Van Norman Reservoir as a normal operating procedure. The inflow to the City system was about 485 cfs from the First Aqueduct and 75 cfs from the Second Aqueduct. Of this total inflow of 560 cfs, the high elevation supply lines which are serviced from points above the complex were taking 40 cfs.

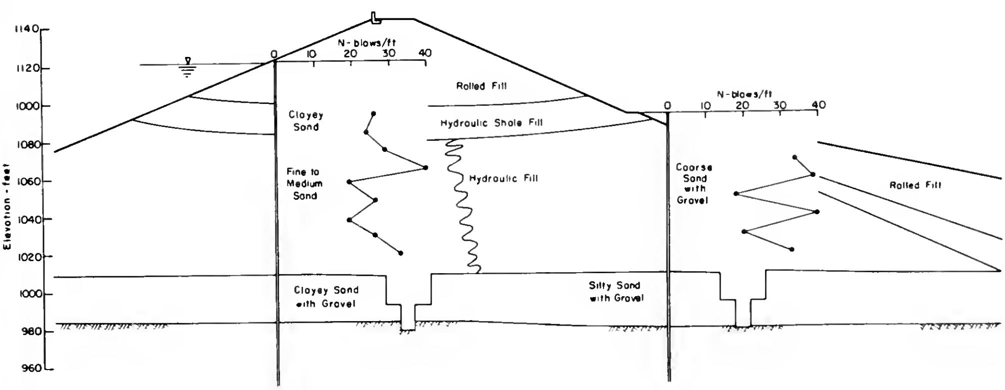


Figure 4. Cross-section through embankment showing soil conditions.

Inflow to the Upper Van Norman Reservoir was 400 cfs. An additional 45 cfs was taken from the Chatsworth High Line at a point between the Upper Van Norman and the Lower Van Norman Bypass Reservoirs leaving 475 cfs going into the Lower Van Norman Reservoir. The Upper Van Norman Reservoir and the Lower Van Norman Bypass Reservoir were both spilling.

The Second Aqueduct was damaged by the 'quake. However, it was being shut down by previous scheduling so that all the flow was from the First Aqueduct, which was immediately closed, resulting in a complete shutdown of water entering the complex. The First Aqueduct, high elevation service lines, the San Fernando Powerplant, and the 42-inch line connecting the 54-inch tower line with the 99-inch Lower Van Norman Bypass line downstream of the dam were all damaged. Drawdown of Upper Van Norman Reservoir was accomplished with flows of 150 cfs through the Chatsworth High Line and between 130 and 225 cfs through two 24-inch-diameter holes cut in the 99-inch-diameter Lower Van Norman Reservoir bypass line where it crosses the spillway chute at the Bull Creek channel. The outlet tower at Upper San Fernando Dam was damaged but standing. The access bridge to the tower had partially fallen into the reservoir, which caused a delay in the closing of that outlet. This evacuation procedure was used to stop the inflow into the Lower Van Norman Reservoir, which was being drawn down as rapidly as possible, and resulted in lowering the water surface of Upper Van Norman Reservoir to about Elevation 1193.

Because of damage to the powerplant, use of the penstock water system was provided by connecting twelve 12-inch steel pipes to the penstock to bypass the powerplant and to allow aqueduct water to enter the Upper Van Norman Reservoir through a temporary standpipe located in the afterbay area. Additional water was delivered via the cascade through a portion of the repaired reservoir bypass channel and was diverted into the afterbay area. Subsequent repairs were made to the remainder of the bypass channel to allow water to enter downstream from the east directly into the reservoir instead of through the afterbay as was done previously. A 120-inch bypass line is being constructed and will be in operation sometime in August 1971.

The drainage system of the Upper San Fernando Dam received an increase in inflow and some structural damage as indicated by the gravel carried through the east contact drain into the measuring vault, which was distorted by the 'quake.

Lower Van Norman Bypass Reservoir

The Lower Van Norman Bypass Dam, which is located along the west side of Lower Van Norman Reservoir, was not damaged by the earthquake of February 9, 1971, except for limited superficial cracking of the asphalt-concrete lining. Minor cracks were observed in the lining on both the upstream and downstream faces of the dam. The dam embankment was inspected at these locations by cutting through the asphalt lining, and no distortion or damage to the dam embankment was found.

At the time of the 'quake, the reservoir was spilling into Lower Van Norman Reservoir. The inflow to the bypass reservoir at this time was 120 cfs from the Upper San Fernando Reservoir, and all this inflow was spilling into Lower Van Norman Reservoir because gates in lines leading off the 99-inch bypass reservoir outlet line were closed. After the 'quake, the operation was modified as soon as possible so as to prevent overflow into the Lower Van Norman Reservoir, which was being drawn down. Fluctuations are now being restricted to elevations below the operating spillway crest and are dependent on downstream service and storage demand.

The drainage system of this dam has not been affected by the 'quake; and the movement and settlement information, together with the surficial inspection, indicate that this reservoir is safe for normal operation.

SOILS INVESTIGATIONS FOLLOWING THE EARTHQUAKE

Immediately following the February 9 earthquake, it was clear that this unusual event required an immediate and thorough investigation. Not only would it be necessary to learn what had happened at the San Fernando Dams, but also why and whether it might happen at other similar dams under similar circumstances. In order to have the most knowledgeable and up-to-date expert information in the field of dynamic soils testing and the analysis of earth embankments under seismic conditions, Dr. H. Bolton Seed, Chairman of the Department of Civil Engineering, University of California, Berkeley, was retained by the Division of Safety of Dams. With the concurrence of the Los Angeles Department of Water and Power, he was requested to formulate and direct a soils investigation of the two damaged San Fernando Dams.

With Dr. Kenneth Lee and others from the University, Dr. Seed immediately laid the groundwork for an investigation program at both dams. A cooperative program was developed jointly with the Los Angeles Department of Water and Power and the California Department of Water Resources. The following paragraphs describe briefly the principal aspects of Dr. Seed's recommended exploration programs.

Lower San Fernando Dam

1. Map, at a scale of 1 inch equals 100 feet, the principal crack patterns on and around the dam, with the aid of stereo aerial photography obtained shortly after the earthquake.
2. Prepare a plan depicting the amount and direction of movement of the component parts of the dam from their original preslide position.
3. Excavate three trenches approximately 5 feet deep transverse to the axis of the dam and 200 to 300 feet apart. Obtain soil samples and make in-place density tests in the bottom of the trenches. Map soil types, stratification, and

other structural features exposed in the sidewalls of the trenches.

4. Drill about 15 or 20 test holes 4 or 5 inches in diameter by rotary methods, in three lines transverse to the dam axis, close to the three trenches or their upstream and downstream extensions. Such holes are to be spaced approximately equidistant from one another, from the upstream face to the downstream toe, and to extend to bedrock or a short distance into bedrock.
5. Obtain undisturbed samples from the drill holes described above, at 5-foot intervals. Obtain penetration resistance values by standard penetration sampler at 5-foot intervals in between the undisturbed samples. For the three holes in the core zone, substitute vane shear testing for the standard penetration resistance testing.
6. Drill large-diameter bucket-auger holes to explore for slide surfaces.
7. Conduct downhole seismic exploration in four to six drill holes to determine shear wave velocity of the different media in and underlying the dam.

Upper San Fernando Dam

The investigation at Upper San Fernando Dam paralleled the one at the lower dam, with the exception of the mapping (items 1 and 2). In addition, the City's need for maintaining the Los Angeles aqueduct system in service has required continued use of the upper reservoir. Therefore, it was drawn down only enough to make immediate repairs then restored to a reduced working level. Thus, exploration is necessarily limited upstream of the crest.

STUDY OF THE LOWER SAN FERNANDO DAM SLIDE

A very preliminary analysis of the major slide which occurred at the Lower San Fernando Dam was made by H. Bolton Seed, K. L. Lee, and I. M. Idriss, based on assumed soil characteristics. The following is briefly adapted from their report.

> **The epicenter of the earthquake, which had a magnitude of 6.6, was located about 8 miles northeast of the damsite, but evidence of fault breaks was found within a mile or so of the dam. Very strong shaking was developed for a period of about 12 seconds, and strong motion records indicate that ground motions in the vicinity of the dam probably had a maximum acceleration of about 0.4 to 0.5 g.**
>
> **The slide occurred on the upstream face of the dam, taking out the crest and the upper 30 feet of soil on the downstream slope. As previously noted, at the time of the earthquake, the water level in the reservoir was about 35 feet below the crest, leaving about 4 feet of soil as the remaining freeboard. Eighty thousand people living downstream of the dam were immediately ordered to evacuate, and the water level in the reservoir was lowered as rapidly as possible; fortunately, no further movements developed. However, the margin by which a major disaster was averted was uncomfortably small. If the City had not been operating the reservoir at a water level lower than normal, if the earthquake shaking had continued for a few seconds longer, or if the Upper San Fernando dam, which moved downstream 5 feet during the earthquake, had released additional water into the reservoir, the remaining embankment could have been overtopped. The Los Angeles Department of Water and Power and the California Department of Water Resources (Division of Safety of Dams) are making detailed studies of the slide to ensure that similar events will not occur in the future.**

Seismic Stability Investigations Prior to the Earthquake

In a general review of the seismic stability of earth dams throughout California, conducted in 1966, the earthquake resistance of the Lower San Fernando Dam was investigated by means of a conventional analysis procedure using a seismic coefficient of 0.15. This value was recommended, based on the known and expected seismicity of the region, by a consulting board appointed by the Los Angeles Department of Water and Power.

The strength of the soil comprising the embankment was determined by means of direct shear and triaxial compression tests on undisturbed samples. The rate of loading in these tests may have been too fast for full drainage of the samples to occur, but the data were interpreted conservatively to provide strength parameters for analytical purposes.

Stability computations were made using the conventional method of slices for the combined effects of (1) an earthquake represented by a seismic coefficient of 0.15 and (2) a partial drawdown of the reservoir level from El. 1125 to El. 1100. These computations showed a minimum factor of safety of 1.01. Using an effective angle of friction of 35° for the sand in the shells of the embankment, the computed factor of safety would have been about 1.08 for a seismic coefficient of 0.1.

Based on the results of these studies, it was concluded that, since the method of analysis was based on conservative strength values and force applications in keeping with conventional practice, the dam was safe against any anticipated ground motion if the water level were not allowed to exceed Elevation 1125. The reservoir has been operated with this restriction during the past few years.

Preliminary Analysis of the Lower San Fernando Dam Slide

The slide which occurred in the Lower San Fernando Dam during the earthquake of February 9, 1971, was due to liquefaction of the hydraulic fill on the upstream side of the embankment as evidenced by the extent of lateral movement of the slide material. Additional evidence of the degree of liquefaction of the soil was also provided by the performance of the pile-supported footing of the footbridge to the central intake tower. After the slide occurred, the slender steel piles, still standing vertically and supporting the footing, projected about 15 feet above the soil below, which had moved horizontally about 70 feet from its original positions. Thus a large quantity of slide material moved around and through these piles without causing any significant lateral deformation; it is difficult to imagine how this could have occurred without a high degree of liquefaction in the surrounding soil. The movement of this foundation also indicates that the base of the slide extended well down towards the base of the embankment.

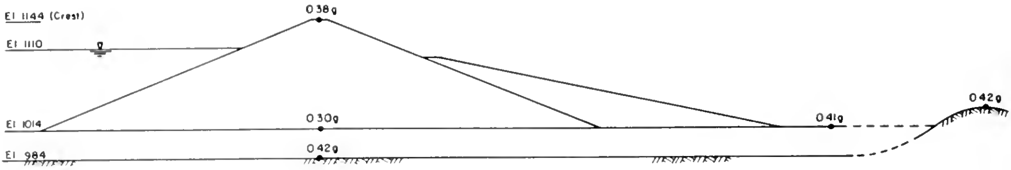


Figure 5. Accelerations computed by response analysis.

A preliminary analysis of the liquefaction potential of the soil in the embankment has been made using the simplified analysis procedure suggested by Seed and Idriss (1970); that is, by comparing the cyclic stress conditions induced by the earthquake with those determined, either on the basis of previous field experience or by laboratory tests, to cause liquefaction of the soil.

Stress Conditions Causing Liquefaction and Evaluotion of Liquefaction Potential

Several years ago, a number of borings were made to determine the characteristics of the embankment soils. It was found that the material graded gradually from a coarse sand and gravel near the outer portion of the shells through coarse sand and fine sand to a clayey core near the center. The main part of the embankment consisted therefore of cohesionless soil ranging from fine sand to sandy gravel with the general characteristics of coarse sand.

An evaluation of the liquefaction potential of the different sections of the embankment may be made by comparing the stress ratios induced by the earthquake with the stress ratio likely to produce liquefaction, previously determined to be about 0.23. For an earthquake similar to the February 9 shock, producing crest accelerations of about 0.4 g, liquefaction would be expected over a substantial depth range under the upstream slope. However, the computed stress ratios show that liquefaction is not likely to develop in the downstream portion of the embankment. This is in reasonable accord with the actual slide movement.

On the basis of preliminary and necessarily approximate analysis, the embankment might have withstood about 10 seconds of ground shaking producing a maximum crest acceleration of about 0.3 g. However, since there are likely to be zones in the embankment where the relative density soil is somewhat less than 55 percent, the maximum crest acceleration for which liquefaction would not have occurred might be of the order of 0.27 g; the corresponding base acceleration would be about 0.20 g.

Similarly, if the relative density of the embankment soils had been about 75 percent, the embankment might well have been able to withstand the intense shaking without liquefaction or detrimental deformation. For earthquakes of greater magnitude, for which shaking would be of longer duration, limiting acceleration would be somewhat lower than indicated above.

While the preceding analysis is grossly simplified, it seems to provide a reasonable picture of the mechanism of slope failure and the conditions causing the major slide in the Lower San Fernando Dam. As further information is developed, based on measurements of site conditions, laboratory determinations of soil characteristics, and more complete determinations of stress conditions within the embankment, it is expected that the mechanics of sliding at the Lower San Fernando Dam will be well defined. Knowledge gained from this investigation should be extraordinarily useful in analyzing the effects of earthquakes on other hydraulic fill dams.

CHAPTER 30

An Engineering Study of the Behavior of Public Utilities Systems in the San Fernando Earthquake of February 9, 1971[1]

by Donald F. Moran [2] and C. Martin Duke [3]

The utility systems are some of the essential "lifelines" of the community. Disruption of these "lifelines" can result in financial loss, disruption of normal and emergency operations, and loss of life.

Financial losses were large (22 million dollars at Sylmar Converter Station alone), and the loss of life among the 80,000 persons living below the heavily damaged Lower Van Norman Dam could have been great (figure 1). Loss of electrical energy and communications crippled emergency operations, and gas leakage caused some nonstructural fires.

Damage to utilities generally followed the same pattern as in past earthquakes. Buried conduits were damaged where permanent earth movements occurred; equipment, when not properly anchored and braced, was severely damaged and some old nonearthquake-resistant buildings and hydraulic-fill dams were nearly destroyed.

One of the most significant aspects of this earthquake is the amount of attention that has been directed toward the behavior of utilities and toward improving the "state of the art" of earthquake engineering of this "lifeline."

Prior to the February 9, 1971, earthquake, the "state of the art" of earthquake engineering in the public-utility sector was low when compared to earthquake engineering of buildings. However, there were some notable exceptions.

Following the Long Beach Earthquake of 1933, several electric utility companies realized the importance of the continuing operation of their critical facilities in the event of a severe earthquake. As a result they adopted increased lateral-force factors in the design of important plants and equipment. They arbitrarily doubled the 10-percent-of-gravity lateral-force factor which was generally being used in codes at that time.

The superior performance, in the February 9 earthquake, of electrical facilities designed in accordance with these conservative standards emphasizes the wisdom of those decisions. There are still some weak links, generally in electrical equipment, that require additional research and the development of design criteria. A re-examination of the arbitrary 20-percent-of-gravity factor is also in order. It would be more reasonable to use the spectral-response approach considering actual earthquake motions and then design for the acceptable level of damage.

Some time after 1933, the telephone companies also adopted lateral-force design criteria for anchorage and bracing of equipment. This practice was effective in that only isolated damage occurred, and that where these criteria were not observed.

Similar steps were taken in the liquid-fuels field and results are encouraging.

Earthquake forces have not generally been considered in the design of buried conduits and other buried structures. Above-ground water tanks have received some attention but need much more.

This report summarizes what utilities existed prior to the earthquake and what damage they sustained. Reasons for the damage are presented where they are known at this time, including relation to permanent ground-movements as they affected utilities.

Recommendations for improvements are not included since they are still in the process of evaluation and development.

The information presented in this report is a brief summary of subcommittee reports for a complete report prepared by the Earthquake Engineering Research Institute (EERI) for the National Oceanic and Atmospheric Administration (NOAA), Department of Commerce.

The authors are indebted to the various subcommittees of the EERI/NOAA San Fernando Earthquake Investigation Committee concerned with utilities, and to the agencies and utilities they represent, for their generous assistance in the preparation of this preliminary summary.

WATER SYSTEMS

Included in this section are supply systems consisting of aqueducts and wells; major distribution systems; storage in dams and tanks; treatment plants; and minor distribution systems. Dams are covered in detail in other papers in this Bulletin (Cortright) and

[1] Manuscript submitted for publication December 1, 1971.

[2] Consulting Structural Engineer, Los Angeles; Chairman, Earthquake Engineering Research Institute/National Oceanic and Atmospheric Administration San Fernando Earthquake Investigation Committee.

[3] Professor of Engineering, University of California, Los Angeles; President, Earthquake Engineering Research Institute.

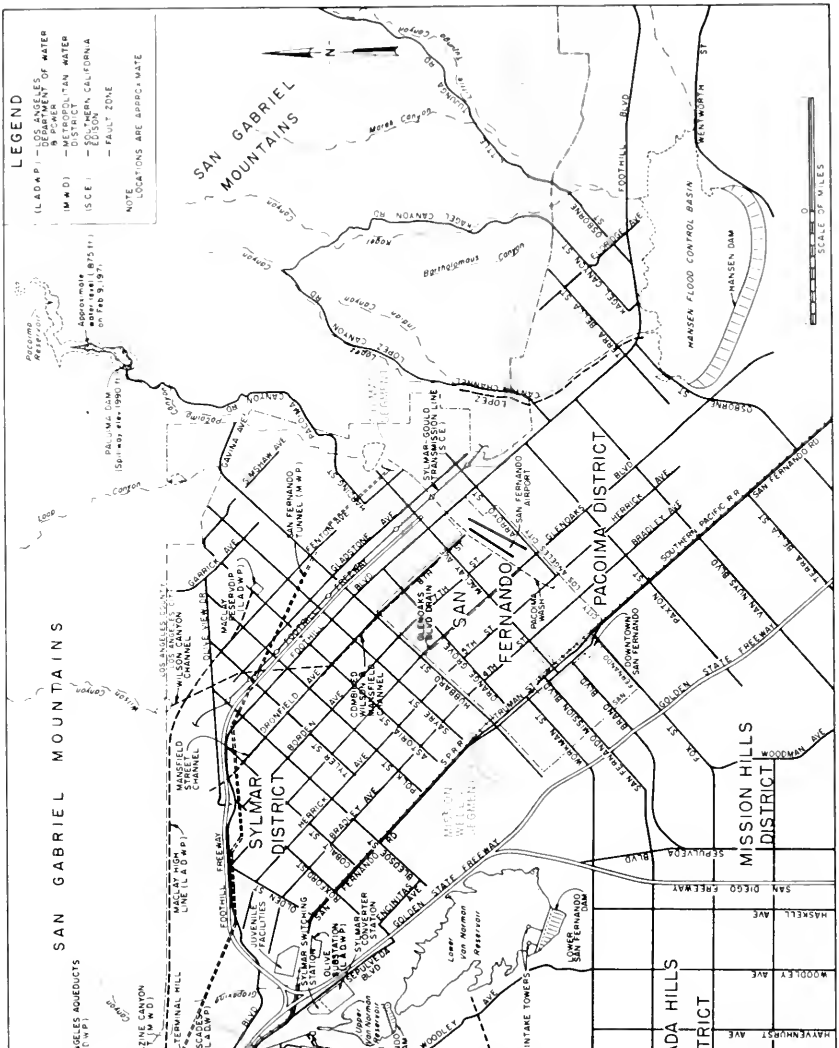


Figure 1. Map of locations of selected utilities.

are included here only in that they are parts of water systems.

Supply Systems

The major supply systems include the California Aqueduct, Metropolitan Water District (MWD) Colorado River Aqueduct, and Los Angeles Department of Water and Power Aqueducts (figure 2).

The California Aqueduct crosses the Garlock and San Andreas faults at several locations in open channel. Other major facilities of this system in the earthquake area include two pumping plants (Oso and Pearblossom) and one dam (Castaic). These structures were designed to resist a static lateral force based on 50 percent of gravity and a vertical force factor of 33 percent of gravity. In addition, articulation was provided in critical areas of civil, mechanical, and electrical features to allow for vertical or horizontal movements that may occur due to the different responses of these features to ground shaking. Inspection conducted immediately following the earthquake revealed no structural damage to any of these facilities, although some suspended light-fixtures in buildings and lightweight shelf-items required some attention.

The Colorado River Aqueduct was not damaged.

Two aqueducts of the LADWP have a terminus in the heavily shaken area (figure 1). The first aqueduct, constructed prior to 1913, was badly cracked in the cascades and in high-speed and by-pass channels but was made operable by February 16, 1971. A 21-mile section of the first aqueduct from the terminus northward was drained and inspected. This section consists primarily of tunnel reaches lined with unreinforced concrete. Inspection revealed hundreds of new fractures in the concrete lining (photo 1). These cracks were repaired by chipping to a depth of 1 inch and resealing with mortar.

A penstock section of the first aqueduct was damaged because of severe vertical and horizontal movement. Reinforced-concrete anchor blocks were shattered as the pipe elongated at two expansion joints. Supporting piers were displaced horizontally and vertically (photo 2).

The second Los Angeles Aqueduct was being shut down at the time of the earthquake. Damage was extensive to the 76-inch-diameter welded-steel part of this aqueduct north of Terminal Hill. A massive slide moved foundations and did serious damage to pipes (photo 3). Repairs to this aqueduct were not completed until April 8, 1971.

The cascades for the second aqueduct are a heavily reinforced concrete box section which sustained only minor cracking.

Wells

Approximately 21 water wells were located in the epicentral area. Eleven of these are owned and operated by the LADWP; seven are City of San Fernando wells; and three are owned by the County of Los Angeles.

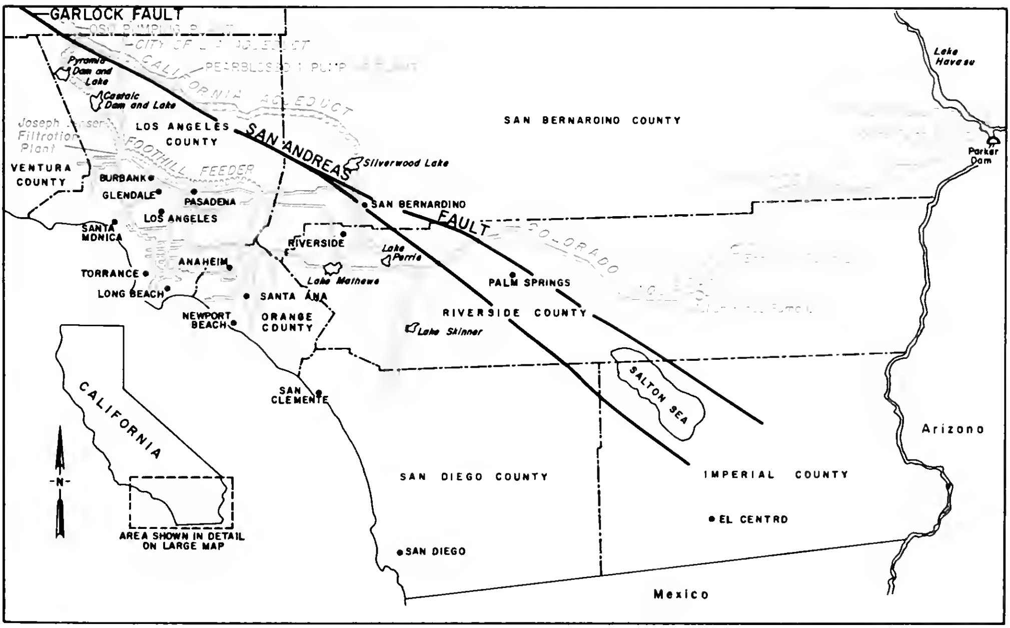


Figure 2. Map of water supply systems.

Photo 1. Aqueduct Division forces repairing fractured areas in tunnel of first aqueduct. *Los Angeles Department of Water and Power photo.*

All of the 21 wells were drilled in the unconsolidated sand, gravel, and finer sediments underlying the relatively flat surface of the San Fernando Valley. The wells are in the area of severe differential ground movement.

Of the 21 wells, 20 withstood the severe groundshaking and movement without any appreciable damage. One well, in the city of San Fernando, was severely damaged by the earthquake. The major impact of the earthquake on the wells in the city of San Fernando was the contamination resulting from damage to well casing, and the many broken sewer lines and septic tanks in the area.

The condition of the wells was judged principally by comparing yield, sand content of water, action of the pump, and the results of bacteriological tests prior to and after the earthquake.

Major Distribution Systems

The Metropolitan Water District and the Los Angeles Department of Water and Power are the only organizations with extensive major water-distribution facilities in the earthquake-affected area. The MWD's 500 miles of distribution pipelines and tunnels outside of this area came through the earthquake with relatively little damage, and delivery of water to the District's 26-member agencies continued without interruption (figure 2). Both agencies, on the other hand, had considerable damage to their major distribution facilities in the San Fernando Valley area.

Photo 2. First Los Angeles Aqueduct penstock. Shattered ancharage pier just north of Upper Van Norman Reservoir.

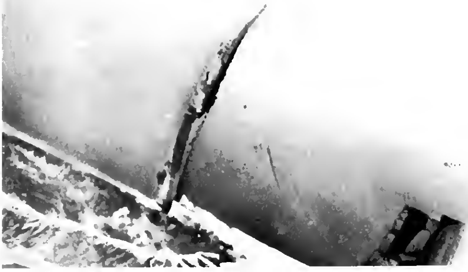


Photo 3. Second Los Angeles Aqueduct. Compression failure in 76-inch Saugus pipeline at mid-slope on north side of Terminal Hill. Note that saddle pier at lower right is displaced downhill as it moved with hill slippage. *Los Angeles Department of Water and Power photo.*

Photo 4. Balboa inlet tunnel. View northeast showing damage to concrete lining. *Metropolitan Water District photo.*

Photo 5. Granada trunk line. One of the more severely damaged welded slip joints. *Los Angeles Department of Water and Power photo.*

The MWD sustained damage to its Balboa Inlet Tunnel and San Fernando Tunnel (figure 1), which were still under construction. The Balboa Inlet Tunnel is 14 feet in diameter and approximately 1 mile long. At a point about 1500 feet from the downstream terminus, this tunnel was damaged for a distance of about 100 feet near the fault crossing. The concrete tunnel lining was badly spalled and cracked, and some of the reinforcing steel was deformed but not broken (photo 4).

The San Fernando Tunnel is 18 feet in diameter and 29,000 feet in length. At the time of the earthquake the tunnel was about two-thirds excavated, being driven from the east portal. Damage was very minor, consisting principally of cracking and spalling of a few of the concrete tunnel supports. However, surveys indicate that the east portal of the tunnel is now 7 feet higher relative to the Magazine Canyon Shaft. This is not expected to have any serious effect upon the hydraulics or the operation of the tunnel, as it will be operated as a pressure conduit.

The LADWP sustained damage to two welded-steel trunk lines; the Granada (photo 5) and Susana Trunk Lines; and two concrete gravity conduits, the Maclay and Chatsworth High Lines. One of the reservoir towers in the Lower Van Norman Reservoir (figure 1) sheared at its base and toppled over while the other stood intact, although it was severely cracked. Neither of these towers had been designed to resist earthquake forces. Two other major lines, also in the area that suffered the greatest damage to other facilities, were not damaged significantly.

Storage Facilities

Table 1 is a partial summary of storage facilities in the area and damage to each.

Damage to old wood roofs is to be expected since they were not designed to resist lateral forces due to earthquakes. Damage to modern welded-steel tanks is disturbing and indicates that better design-criteria must be developed.

The damage to the underground concrete-finished water reservoir at the Jensen Filtration Plant poses an interesting problem. Prior to this earthquake, antiseismic design of underground structures received little attention. Behavior of the finished water reservoir was apparently much like buildings above ground. The roof diaphragm failed at pour-lines adjacent to exterior walls, and subsequent lateral movements caused damage to exterior walls and interior columns (photos 6 and 7).

Photo 6. Joseph Jensen Filtration Plant, finished water reservoir. West wall at left, showing damage. Note failure at construction joint in roof and damaged columns. *Metropolitan Water District photo.*

The failure of the Lower and Upper Van Norman Dams is covered in detail in other papers. (See Cortright, this Bulletin). These are hydraulic earth-fill dams originally built during 1912 to 1915. Loss of reservoir capacity due to near-failures of these dams has seriously reduced water storage capacity in this area.

None of the compacted-fill debris dams in the region of strong shaking sustained any significant damage, though there was some damage to their spillways and outlet structures. Some transverse cracking was found at the crest of some of the dams, due perhaps to a "whipping" action during the earthquake. Exploration indicated that the cracks were shallow and did not affect the integrity of the structures. The concrete-arch Pacoima Dam, on a rock foundation, withstood the strongest ground motion ever recorded without significant damage to the concrete structure.

Treatment Facilities

The largest treatment plant in the heavily shaken area was the $45-million Joseph Jensen Filtration Plant which was under construction and about 85 percent complete (figure 1).

Damage to portions of the plant was extensive, particularly in the area of the finished water reservoir (discussed previously under storage facilities) and portions of the effluent conduit. A major landslide occurred in the fill area at the southeast portion of the site. This slide had a plan dimension of about 2500 feet by 800

Table I. Water storage tanks (partial listing)

Name and owner	Location	Size	Construction (construction date)	Damage
Sesnon (LADWP)	Porter Ranch (4 mi. west of Upper Van Norman Reservoir)	92 ft. in diameter by 42 ft. high	Welded steel. (20% gravity design)	Fill settlement prior to and during earthquake. Horizontal buckle in shell plate 24 feet from bottom along about 150° sector. 95 percent full. *Photo 8*
Maclay Reservoir (LADWP)	Figure 1	280 ft. square	Earth dike. Wood roof. (1917)	Roof structure collapsed. 80 percent full.
Granada High Tank (LADWP)	Porter Ranch (2.2 mi. west of Upper Van Norman Reservoir)	55 ft. diameter by 45 ft. high	Riveted steel shell. Steel roof trusses. (1929)	Collapse of roof trusses. 73 percent full. *Photos 9 and 10*
Wash Water Tank (MWD)	Joseph Jensen Filtration Plant	100 ft. diameter by 36 ft. high	Welded steel (1971)	Buckling of tank shell. Anchor bolts pulled out of concrete ringwall. About ½ full at time of earthquake. *Photos 11 and 12*
Finished Water Reservoir (MWD)	Joseph Jensen Filtration Plant	520 x 500 ft. 35 ft. water depth	Buried reinforced concrete (under construction)	Roof diaphragm failed at construction joints. Walls failed at bottoms. Many supporting columns were badly damaged due to bending. About ⅔ of 7-foot-thick fill on roof in place at time of earthquake. *Photos 6 and 7*
City of San Fernando Tanks #1	4th St. @ Hubbard	50 ft. diameter by 12 ft. high	Concrete-lined embankments. Wood roof. (About 1920)	10 ft. of water at time of earthquake, wood roof collapsed. Concrete lining cracked.
#2	Dronfield Ave. @ Hubbard	195 x 210 ft. Rectangular by 12 ft. deep	Concrete-lined embankments. Wood roof. (About 1920)	10.5 ft. of water at time of earthquake, wood roof collapsed. Concrete lining cracked.
#3	Foothill Blvd. @ Hubbard	50 ft. diameter by 12 ft. high	Reinforced concrete walls. Wood roof. (1962)	10 ft. of water at time of earthquake. No damage.
#4	Foothill Blvd. @ Hubbard	78 ft. diameter by 31 ft. high	Reinforced concrete walls and roof. (1962)	29 ft. of water at time of earthquake. Damage to piping only.
#5	Dronfield Ave. @ Hubbard	163 ft. diameter by 17 ft. high	Reinforced concrete walls and roof. (1962)	15 ft. of water at time of earthquake. Horizontal cracks in walls.

feet and had its base in natural soil about 40 to 60 feet below the general ground surface. Based upon observations of ground surface-cracking, the north portion of the slide pivoted about its southern end with a total easterly movement of about 3 to 5 feet.

This landslide had a detrimental effect on structures. Most of the existing exposed and buried structures in the north area of the slide moved eastward on the order of ½ to 1 foot, causing many expansion joints to open.

The south area of the site contained the finished water reservoir, effluent conduit, overflow conduit, and the Bee Canyon storm drain. The damage to the effluent and overflow conduits (photo 13) and the storm drain consisted primarily of slight to moderate distress in joints which opened ½ to 3 inches.

The mixing and settling basins are underlain by compacted fill ranging in thickness from a knife edge near the middle of the settling basins to approximately 30 feet at the east end of the mixing basins. Settlement of the basins was in direct proportion to the fill depth, up to about 5 inches at the east wall of the mixing basins. Structural distress of the basins was minor and consisted basically of opening of expansion joints and minor joint spalling, as well as damage to the launder troughs which had not yet been secured to the columns (photo 14).

The chemical building sustained failures of structural-steel members (photo 15). The service-center building had fairly severe cracking and spalling at wall-to-floor connections, particularly where the two wings of the building connect.

A survey of the LADWP's water-distribution treatment facilities showed that there were two critical locations, the Granada Hills and the Sylmar sections. Evaluation of the conditions of the distribution system

Photo 7. Joseph Jensen Filtration Plant, finished water reservoir. View of west wall, toward south. *Metropolitan Water District photo.*

and of the effectiveness of the chlorination treatment suggested that there was no damage to the supply although the outflow from Lower Van Norman Reservoir was turbid.

All chlorination and treatment installations were reported operating, and no serious damage was found. The Van Norman area lost the operating power supply and had to operate on emergency equipment. Power was lost at the Maclay High Line Chlorination Station, and emergency equipment was used.

The recently completed program of securing all chlorine cylinders by chains and load-binders undoubtedly prevented broken connectors, damage to the chlorination facilities, and release of chlorine liquid and gas.

After the initial inspection of facilities, emergency operating procedures were started. Chlorine dosage was increased in some systems. Emergency chlorination operations continued until the restoration of the distribution system throughout the Sylmar area.

Minor Distribution Systems

The damage to potable water distribution system seriously disrupted the supply in Sylmar and San Fernando. Broken underground piping interrupted service, requiring the use of tank trucks to haul emergency supplies. Fortunately the total area so affected was small and there was ample water which could be piped in from outside areas.

A portion of the pipeline damage map is shown as figure 3. Concentration of damage can be identified with the Sylmar fault segment (figure 1).

The City of San Fernando operates and maintains a municipally owned system consisting of seven wells, five reservoirs, and necessary collection-and-distribution piping. One 6-inch emergency connection was

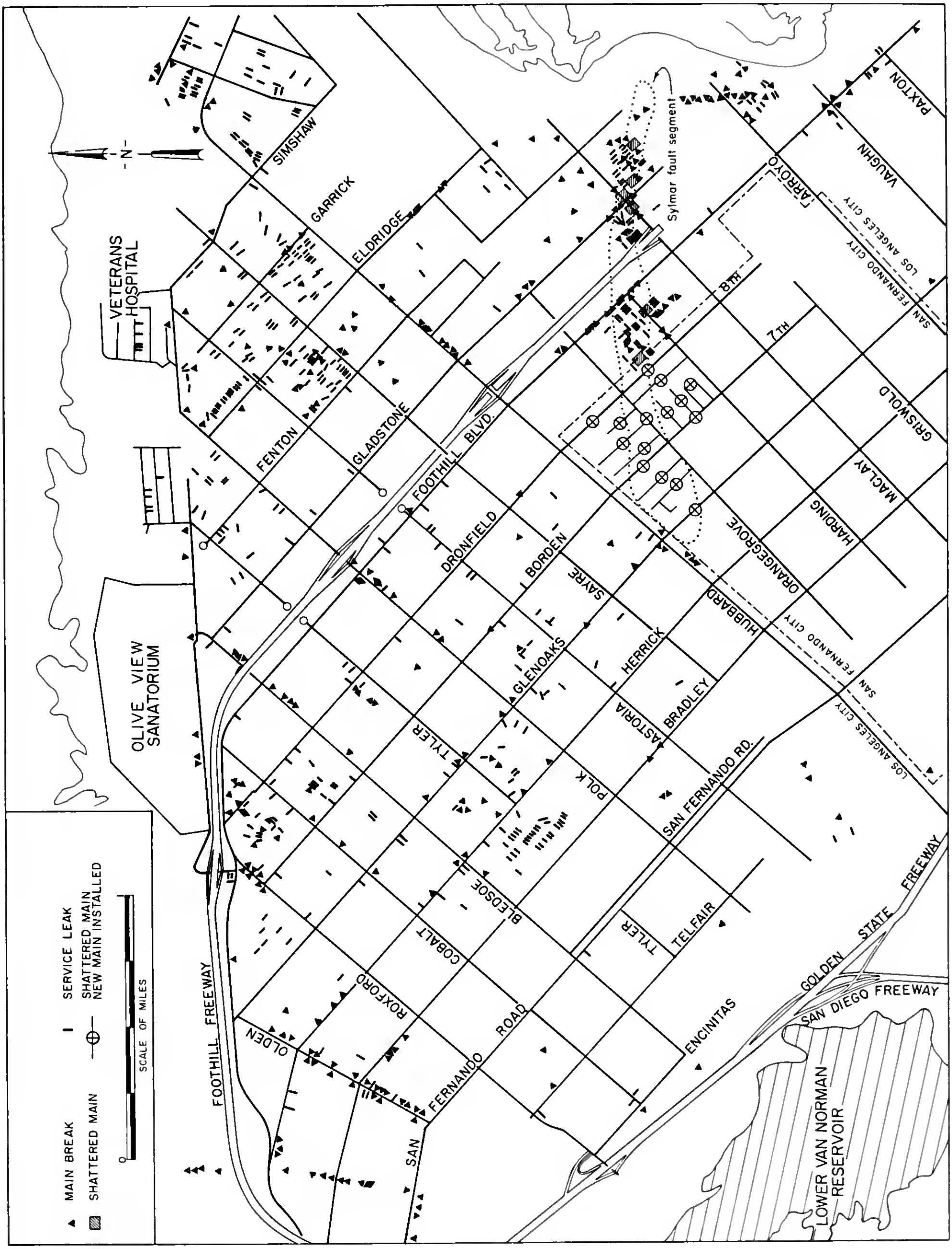


Figure 3. Map of part of the water pipe damage.

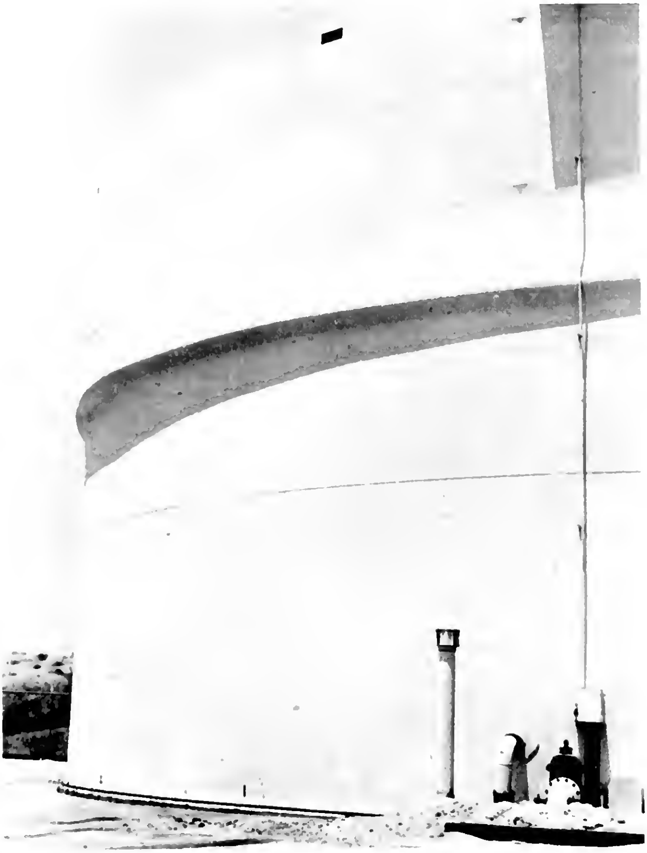


Photo 8. Sesnon Tank. Close-up showing buckle at about mid-height. *Los Angeles Department of Water and Power photo.*

maintained with the City of Los Angeles system for backup.

Earthquake damage to the water lines in San Fernando occurred mainly in the northwestern corner of the city. This area is bounded by Eighth Street on the north, Glenoaks Boulevard on the south, Orange Grove Avenue on the east, and Hubbard Avenue on the west and is within the zone of intense surface rupturing (figure 3).

In the extreme northern section of San Fernando, the U. S. Army Corps of Engineers replaced the heavily damaged underground piping with a surface system. In other city areas the Metropolitan Water District, City of Pasadena, City of Burbank, and City of Long Beach furnished emergency repair crews and MWD temporarily connected to one of their supply lines.

The principal damage in the water lines was to the pipe joints which were crushed; bells and spigots were broken; and joints opened and misaligned (photo 16). The most prevalent damage to uncoated-steel water mains was very small holes resulting from internal water pressure on pipe walls weakened by corrosion and earthquake movement. There was some damage where pipe-repair clamps had been installed.

There was widespread damage to cast-iron pipe, taking the form of circumferential cracks resulting from the earth movement. In locations where the movement of the earth was more pronounced, some cast-iron mains were shattered. Most joint failures in both steel and cast-iron mains were cement-caulked.

The bodies of some automatic vacuum-breaker and air-release valves were cracked. In others the ball float was crushed by the surge of water. The bell connections of a number of gate valves, elbows, tees, and offsets were broken off.

The major cause of damage to service lines to individual customers was the rigidity of the parts and connections. Vertical and horizontal ground-displacement sheared off ball-and-socket elbows and meter

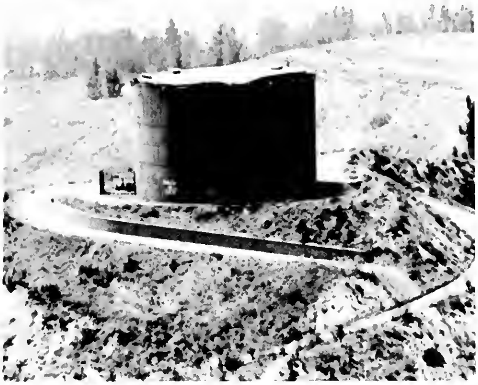


Photo 9. Granada High Tank. Over-all view of tank. Note damaged roof. *Los Angeles Department of Water and Power photo.*

connections; broke service clamps, corporation and curb valves, and tubing on copper services; and caused the breakage and distortion of the meter casings. The rigidity of galvanized lines resulted in the breakage of elbows, couplings, and pipe.

Compression and tension stresses ruptured joints and broke meter inlet and outlet connections (photo 17). Water-meter gaskets were blown by water surges.

The collapse of the East Outlet Tower at the Lower Van Norman Reservoir caused sand and debris to enter the water distribution system and damage the water-meter pistons, causing them to stick, making the meter inoperable.

Storm Drains

There was substantial damage to portions of Wilson Canyon Channel, Mansfield Avenue Storm Drain,

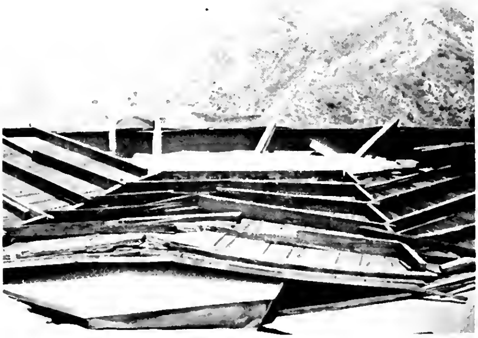


Photo 10. Granada High Tank. Close-up of collapsed roof which was originally of a low profile, conical shape. *Los Angeles Department of Water and Power photo.*

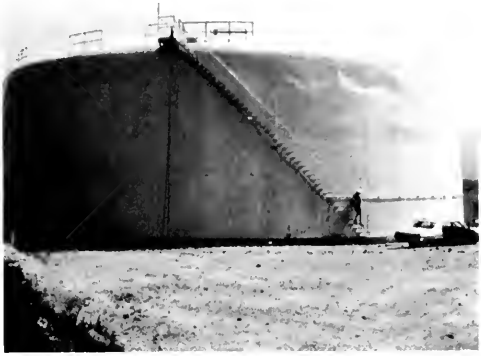


Photo 11. Joseph Jensen Filtration Plant, wash water tank. Note wrinkle in shell in top course.

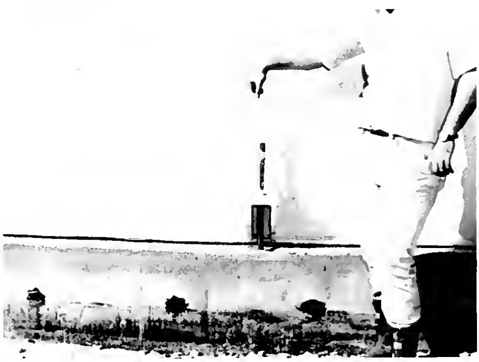


Photo 12. Joseph Jensen Filtration Plant, wash water tank. Anchor bolt on south side was pulled about 11 inches from foundation wall. *Metropolitan Water District photo.*

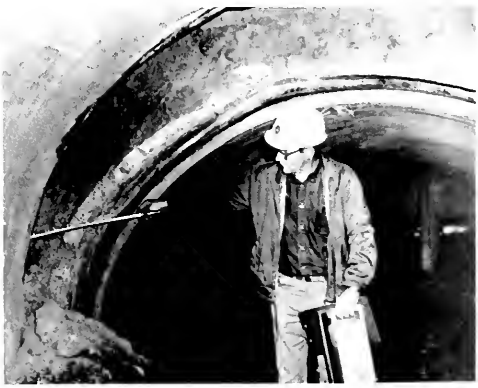


Photo 13. Joseph Jensen Filtration Plant, reservoir 96-inch diameter overflow pipe. First pipe joint from east end separated about 2 feet in offset. *Metropolitan Water District photo.*

Pacoima Wash, Lopez Canyon Channel, and Glenoaks Boulevard Drain, all in the San Fernando-Sylmar area (figure 1).

There were separations of concrete-box culverts; catch basins were damaged; there was extensive spalling of concrete; concrete channel-walls were displaced; and in one case, a 12- by 22-foot reinforced concrete box structure failed over a length of about 500 feet where it crossed the fault (photo 18). Damage was associated with permanent ground movement and not with vibration.

Sewers

The sewers were damaged in the zones of faulting and ground cracking. The pattern of damage was roughly the same as for the water lines (figure 3). The types of sewer-system damage included broken pipe, broken joints, pulled joints, changes in grade, and shifted and cracked manhole structures. Essentially none of the sewer damage could be attributed directly to ground shaking.

In general, the more flexible plastic compression joint suffered less damage than the more rigid type joints. Also, larger pipes sustained greater relative damage than the smaller pipes. The principal damage was probably caused by permanent ground displacement rather than vibration, although hairline cracks in pipes undoubtedly resulted from vibration.

Television inspection of the area's sewers was necessary to assess the damage. It is estimated that about 20 percent of the sewers will require replacement or reconstruction. Despite the extensive damage, all sewers were kept in operating condition through emergency repairs pending the necessary permanent reconstruction.

ELECTRICAL UTILITIES

Since the Long Beach earthquake of 1933, most California electrical utilities have developed antiseismic

Photo 14. Joseph Jensen Filtration Plant. Launder columns and launders in west end of south settling basin. Launders fell from atop columns. *Metropolitan Water District photo.*

Photo 15. Joseph Jensen Filtration Plant chemical building. Buckled steel bracing member.

criteria for the design of important and critical facilities. These criteria are generally in excess of those required by local building codes. The behavior, in this earthquake, of facilities designed under these conservative criteria was good. The most dramatic weaknesses were in the behavior of electrical equipment. Most of this equipment was purchased under specifications which required a lateral-force resistance of about 20 percent of gravity, but the resulting designs or installations were inadequate to resist the strong lateral forces in the epicentral area. Included in this section are generating facilities, transmission lines, terminals, switching stations, distributing stations, and distributing systems.

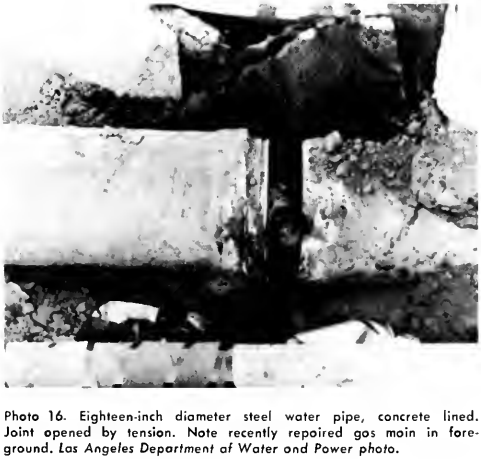


Photo 16. Eighteen-inch diameter steel water pipe, concrete lined. Joint opened by tension. Note recently repaired gas main in foreground. *Los Angeles Department of Water and Power photo.*

Electrical Generating Facilities

The Valley Steam Plant (LADWP) with a generating capacity of 512,000 Kw is located about 10 miles south of the epicenter. This modern plant, including all equipment, was designed to resist lateral forces equivalent to about 20 percent of gravity. Behavior in the earthquake was remarkably good, the only damage being one broken lightning arrester. Maximum ground acceleration in this area is estimated at 30 to 40 percent of gravity.

The San Fernando Hydroelectric Generating Plant No. 3 (LADWP), is a small (6000 Kw) facility located just north of the Upper Van Norman Reservoir. This old reinforced-concrete structure, built in 1927, was not designed to resist earthquake forces. The area beneath and surrounding the plant subsided approximately 2 feet during the earthquake. The structure was undermined by water because of a break in the inlet penstock near the turbine case under the building. Structural damage was severe.

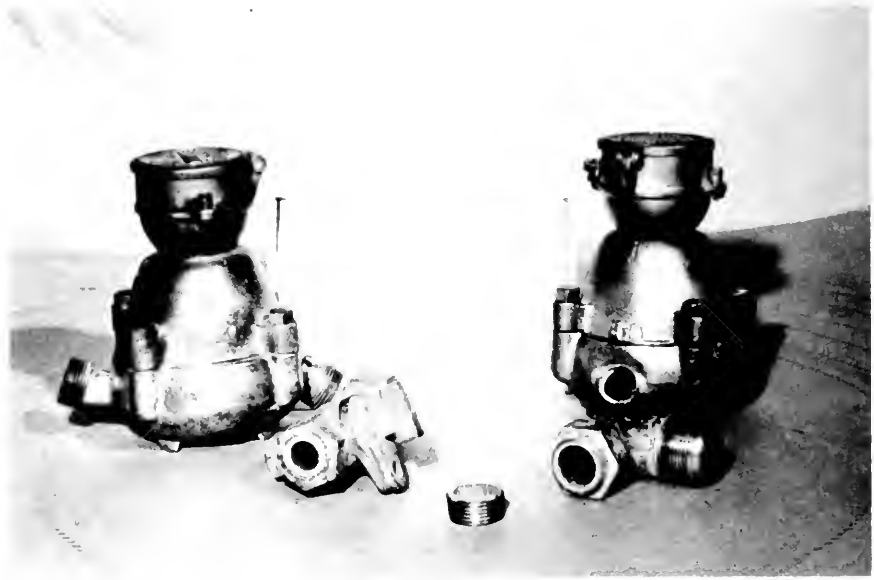


Photo 17. Water meters broken in earthquake. *Los Angeles Department of Water and Power photo.*

Two hydroelectric generating plants (LADWP), located in San Francisquito Canyon about 14 miles north of the epicenter, sustained only minor damage. They were constructed in 1917 and 1920 of reinforced concrete without specific antiseismic features.

The San Onofre Nuclear Generating Plant is the only major nuclear power facility within the general area. Located about 83 miles south of the epicenter, it was not damaged. Maximum acceleration recorded at the site was only 2 percent of gravity. Several nuclear-research reactors in the Los Angeles area performed well in this earthquake.

Transmission Lines

Towers for transmission lines are designed for heavy lateral forces due to wind and for loads due to broken-conductor conditions. None sustained damage because of ground shaking, except as noted below.

About 49 towers of the LADWP were affected by earth displacement and fissuring. The foundations of 19 towers were displaced enough to bend and damage steel members within the towers. Where transmission lines cross a known fault, conductors are placed perpendicular to the fault trace so as to minimize change in span length due to fault movement.

Approximately 88 towers of the Southern California Edison Co. (SCE) were affected by earth displacement. They required excavation, grading backfill, and compaction. A number will require crib walls. Tops of two partially erected towers toppled over on the Sylmar-Gould line which was under construction (figure 1). These two towers of contemporary design had been temporarily bolted together the night before the earthquake, in preparation for final welding.

Electrical Terminals

The Sylmar Converter Station is the major electrical terminal in the Sylmar-San Fernando area, serving as the southern terminus of the Pacific intertie. This high voltage converter station is located just east of the Upper Van Norman Reservoir (figure 1). The area was affected by lateral and vertical soil movement associated with a large areal movement referred to by some as the Juvenile Hall Slide. Permanent lateral movements at the converter station amounted to 3 to 5 feet in a westerly direction. In the same area, there were differential lateral and vertical permanent ground deformations due to faulting. Surveys made after the earthquake have confirmed the presence of differential lateral and vertical ground movements in these areas. Many breaks occurred in underground conduit runs.

The damage to building structures would not in itself have caused shutdown of the terminal. However, massive damage to electrical equipment at this location will require 18 to 24 months to repair or replace and comprises the major portion of the estimated 22-million-dollar loss—about 40 percent of total value.

The building structures at the converter station, designed for 20 percent of gravity, suffered only minor damage. The service building and valve hall are two separate steel structures above the first floor. However, below the first floor there is no separation. Most

Photo 18. Mansfield-Wilson flood control box. Horizontal cracks in concrete wall generally occurred at reinforcing bars. Note vertical offset in roof slab. Damage occurred in area of fault movement.

Photo 19. Sylmar Converter Station, radio interference structure. Broken diagonal bracing connection.

Photo 20. Sylmar Converter Station, radio interference structure. Concrete apron wall pulled away from concrete pedestal.

of the damage occurred in the basement area under the building separation. There was some settlement of basement walls.

Bracing members and low concrete-apron walls of two large, open, steel-frame structures (each 300 by 326 by 60 feet high) used to support radio interference screens on the east and west sides of the main intertie building were severely damaged by ground movement (photos 19 and 20). These structures are light; bracing was adequate to resist lateral forces in excess of 100 percent of gravity. Other considerations, such as wind, governed the bracing design.

In general, the damage to electrical equipment was caused by ground vibration rather than permanent soil movements.

All of the 42 mercury-arc valves and current dividers in the valve bay were damaged (photos 21 and 22). The current dividers, weighing about 8000 pounds each, were hung by four insulators from the roof framing and were connected to the valves below. The valves were supported on platforms supported by vertical insulators resting on the floor.

Failure occurred at the insulator suspensions of all of the current dividers, and several fell to the floor. Swinging movements of the current dividers damaged connections to the valves, and falling dividers caused severe damage to the valves. None of the valve-support insulators were damaged.

In the outdoor yards, there was severe damage to air circuit breakers, filter reactors, and filter capacitor racks (photos 23–26).

Analysis has indicated that the air circuit-breakers which have heavy heads on single tall porcelain columns have natural periods in the range which are amplified by periods identified in ground motion records of the earthquake.

The brittle insulator materials were unable to withstand significant bending loads.

Vincent 500 Kv Substation, Southern California Edison (SCE), with some similar equipment, sustained only minor damage to electrical equipment. This station is about 16 miles northeast of the epicenter.

Switching Stations

The Olive Switching Station (LADWP), located half a mile east of the Sylmar Converter Station (figure 1), was put out of service totally. Seven transformers toppled on their sides, and other equipment was severely damaged (photo 27). The transformers and equipment were not adequately anchored.

Other switching stations of LADWP and SCE were damaged in varying degrees, including the Sylmar Switching Station just north of the Sylmar Converter Station where all of the live tank air circuit breakers were damaged.

Substations

Major structural damage was sustained in four distribution substations. Enclosing cantilevered walls of two modern stations were structurally damaged, but none collapsed. Unreinforced brick walls of two

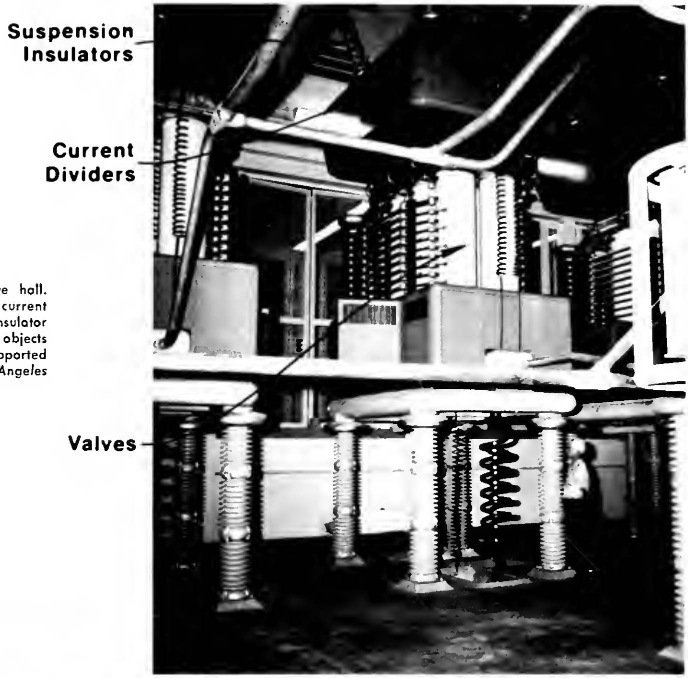


Photo 21. Sylmar Converter Station, valve hall. Picture taken before earthquake, showing current dividers hung from roof structure by insulator strings. Mercury arc valves are cylindrical objects below current dividers. Arc valves are supported from floor on insulator pedestals. *Los Angeles Department of Water and Power photos.*

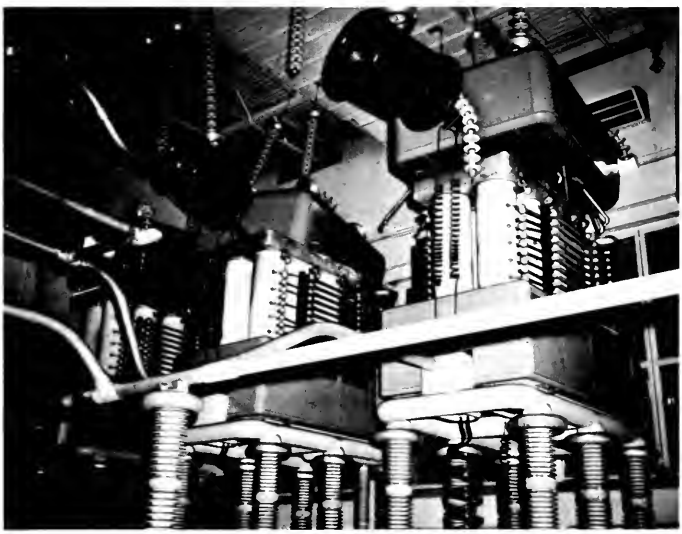


Photo 22. Sylmar Converter Station, valve hall. Picture taken after earthquake. showing broken insulators which supported current divid ers. Note damage to electrical connections between current dividers and valves below. *Los Angeles Department of Water and Power photo.*

Photo 23. Sylmar Converter Station. Pneumatic circuit breakers. Two relatively undamaged units in foreground. *Los Angeles Department of Water and Power photo.*

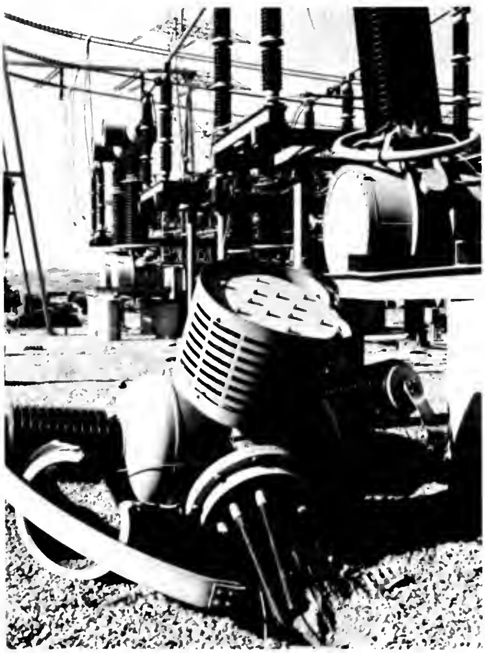


Photo 24. Sylmar Converter Station. Head of pneumatic circuit breaker. Note broken wooden rods in foreground. *Los Angeles Department of Water and Power photo.*

old, non-earthquake-resistant distributing stations in downtown Los Angeles were severely damaged. Electrical equipment was damaged at five substations, including synchronous condensers, transformers, switches, lightning arrestors, and two air-blast circuit breakers.

Distribution Systems

Some 285 small distribution transformers were so damaged as to have to be replaced. These were almost all overhead pole mounted transformers (photo 28). Thirty wood poles required replacement.

There were about 240 primary wires down and 450 feeder outages.

All power to customers was back in service by February 12, 1971.

GAS SYSTEMS

The San Fernando-Sylmar area is supplied with natural gas by the Southern California Gas Company. Pacific Lighting Service Company, an affiliate, operates transmission lines in the San Fernando-Sylmar area as well as throughout most of southern California.

Transmission Systems

A portion of the transmission system, handling the deliveries of California gas from San Joaquin Valley south to the Los Angeles Basin, was damaged to the extent that four welded-steel lines had to be shut down in the San Fernando area. Damage to the four 12- to 26-inch lines occurred between Newhall and San Fernando and resulted in the loss of gas supply in the San Fernando-Sylmar area.

The greatest damage was sustained by a 16-inch transmission line in Foothill Boulevard and Glenoaks Boulevard. In this 6-mile length of pipeline, there were 52 separate breaks (photo 29). Five miles of a 12-inch transmission line have been abandoned between Sylmar and San Fernando due to numerous breaks. Nine breaks occurred in a one-mile length of a 26-inch transmission line in the Sylmar area. Over all, a total of 68 transmission-line breaks were repaired in restoring service. Control of gas flowing through the area was accomplished by closing main-line valves on the affected pipelines except for one break where the leakage was monitored but allowed to continue to prevent additional customer outages. Continuation of supply to the Los Angeles Basin area was also aided by an eight-hour curtailment of large steam-plant loads in the San Fernando Valley area.

Distribution Systems

The gas-distribution pipe system was seriously damaged within an 11-to-12-square-mile area in the northeast section of San Fernando Valley including Sylmar and the city of San Fernando. This triangular area is bounded on the west by the Golden State Freeway, on the south by the Pacoima Wash, and on the north by the San Gabriel Mountains. The distribution facilities within this area were supplied mostly by the damaged transmission lines described above.

Photo 25. Sylmar Converter Station. Harmonic filter fell over. Anchorage to foundations failed.

Photo 26. Sylmar Converter Station. Toppled filter capacitor banks. *Los Angeles Department of Water and Power photo.*

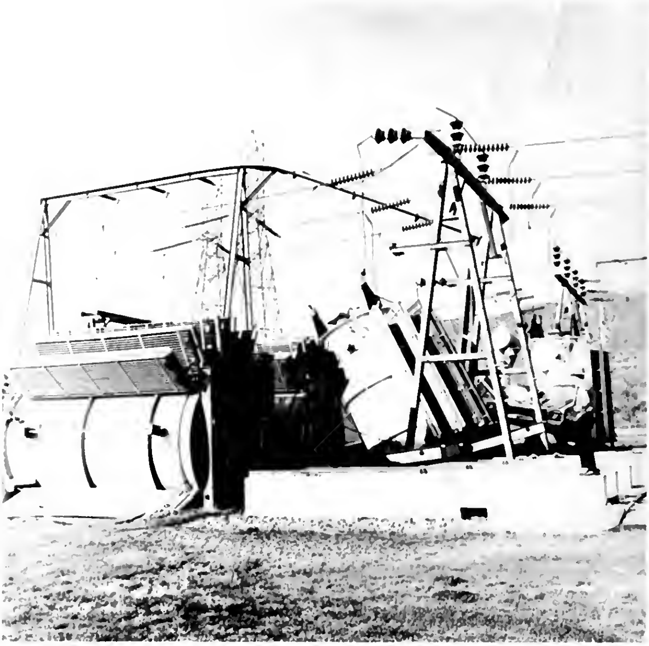


Photo 27. Olive Switching Station. Toppled transformers. *Los Angeles Department of Water and Power photo.*

Photo 28. Damaged pole-mounted transformer on ground. *Los Angeles Department of Water and Power photo.*

Photo 29. Compressive forces buckled 16-inch steel gas pipeline and 10-inch tee. ***Southern California Edison Company photo.***

Supply was lost to eight distribution regulator stations supplying some 17,000 customers.

Only two or three fires occurred in the streets at broken gas lines. Fire damage to structures due to gas leakage was minor.

The distribution system in the hard-hit area consists principally of 2-, 3-, and 4-inch welded-steel mains and ¾-inch welded-steel service lines. Service was generally restored in the hard-hit area by February 22, 1971.

Damage to gas lines was caused principally by permanent ground movement. The areal pattern of breaks was generally consistent with that for other types of underground conduits.

OIL AND GASOLINE FACILITIES

A 4-inch and an 8-inch crude-oil line were separated in the zone of faulting in the Sylmar area. There were a few minor leaks and floating-roof dislocations in storage tanks, but no leaks in underground distribution tanks were evident. Several service stations were structurally damaged, but none collapsed. Refineries had very minor damage, and some wells increased their productivity.

This industry has been working on improvements in antiseismic design standards since 1933.

COMMUNICATION SYSTEMS

Communications systems include telephone, radio, amateur radio, and television facilities. The worst damage was to poorly anchored telephone-switching equipment. Damage to modern telephone buildings and other communication facilities and equipment was minor. However, there were interruptions of service due to power-supply outages.

Telephone

The area affected by this earthquake is served by the Pacific and The General Telephone Companies. The General Telephone Company sustained the worst damage at their Sylmar Central Office. Ninety-five percent of the automatic switching equipment was buckled or bent, lying on the floor or against adjacent frames and/or walls (photo 30). This damage was caused by the heavy shaking and inadequate anchorage of the equipment to the building.

To speed repairs, the damaged equipment was removed completely from the building (photo 31).

Damage to this facility affected 9500 customers. Service was restored by March 19, 1971, about 5 weeks after the earthquake.

There was minor damage to telephone equipment at other locations such as the Newhall Central Office where flooding due to a ruptured water main caused a temporary shutdown.

Modern buildings housing telephone facilities generally sustained only minor damage. Older non-earthquake-resistant telephone structures were moderately damaged.

Overloading of telephone circuits caused partial breakdown of the Los Angeles system.

Telephone companies have been aware of potential earthquake-damage to equipment for many years. They have adopted criteria and developed details for anchorage and bracing of equipment. Evidently some of the criteria and details require improvement in design and installation.

Radio and Television

Power failure to receivers caused communication blackouts in the heavily damaged area, except via battery-operated sets, including radios in automobiles. A television station in Burbank was forced to use its truck-mounted auxiliary transmitter.

Amateur radio, of use in lieu of malfunctioning telephones, was not curtailed by the 'quake except where electrical power was out.

SUMMARY AND CONCLUSIONS

In general, the "state of the art" in utility or "lifeline" earthquake engineering is at a relatively low level as compared to structural building earthquake engineering, although there are some important exceptions.

This earthquake has stimulated considerable activity in the "lifeline" earthquake-engineering field, and significant progress should result as this stimulation is carried through to improvements in criteria and construction practices.

The lessons learned from this earthquake are not significantly different from those learned from recent past shocks. However, there was a concentration of

Photo 30. Sylmar Central Office. Collapsed automatic telephone switching equipment. *General Telephone Company photo.*

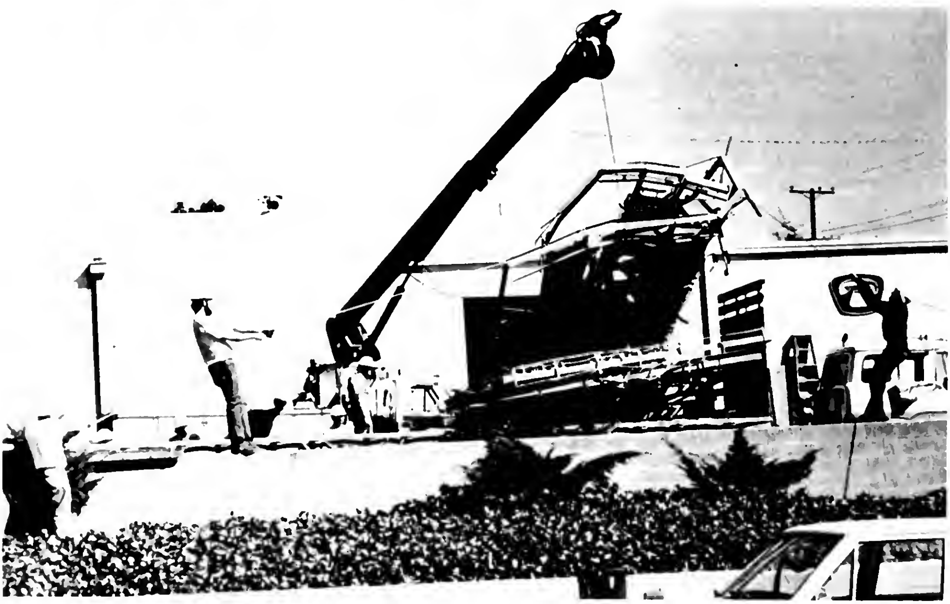


Photo 31. Sylmar Central Office. Collapsed automatic telephone switching equipment being removed from building. *General Telephone Company photo.*

modern utilities in the heavily shaken area which provided a good test of present practices. The main lesson reiterated is that structures and equipment must be specifically designed, detailed, and constructed to resist strong seismic forces in order for them to escape damage in an earthquake. Poorly designed, detailed, and constructed facilities are ferreted out by earthquakes and the "weak links" are exposed.

Several conclusions can be reached:

1. Modern steel water-storage tanks and old water-reservoir roof structures performed poorly. Old hydraulic earth-fill dams, not designed to resist earthquake loads, performed poorly, with two experiencing near-failure.

2. Underground conduits for water, sewage, storm-water, gas and petroleum were damaged, mainly because of permanent differential ground-movements rather than due to vibration. Effective preventive measures in this field will be difficult to develop. Potential ground-movement areas should be identified.

3. Large underground structures such as the Finished Water Reservoir at the Joseph Jensen Filtration Plant require special attention. Apparently they act much like structures above grade. More research is needed, along with development of design criteria.

4. Electrical power equipment performed poorly. Failures were due to inadequate anchorage and bracing and in some cases to inadequate aseismic details within the equipment.

5. Communication equipment in the telephone industry performed well except for several failures due to inadequate or poorly detailed and constructed anchorages and bracing.

Section 4

Disaster Response

CHAPTER 31

Emergency Operations for Earthquakes*

Emergency operations, following the San Fernando earthquake, were those measures and actions taken by local government departments and agencies, the American Red Cross and nongovernmental agencies and associations to save lives, aid the injured, preserve property, mitigate hardship and expedite recovery.

The earthquake provided a test of the ability of these organizations to cope with an emergency. Also it was an opportunity to evaluate emergency plans and procedures. For these reasons the Commission reviewed in considerable detail the emergency operations that were conducted after the earthquake. The Commission's investigation, although centered on the actual conduct of operations, included study of the legal basis for coordination.

Federal financial assistance was provided local governments and individuals under Public Law 91-606, the Disaster Relief Act of 1970, and other applicable public laws, but this category of assistance was not reviewed in detail.

Operations, in general, were well conducted and effective, but every disaster points the way to making improvements in plans, procedures and preparations for such contingencies. The Commission's recommendations with respect to emergency operations are directed to this end.

LEGAL BASIS

The legal basis in California for local government emergency operations is the California Emergency Services Act of 1970.

Local governments normally enact ordinances providing for their emergency duties and functions.

CALIFORNIA MASTER MUTUAL AID AGREEMENT

The basis for providing mutual aid among local governments and the State is the California Master Mutual Aid Agreement. The signatories thereto agree to provide assistance to each other whenever the conditions of disaster or of extreme peril are, or are likely to be, beyond the control of the services, personnel or equipment of the affected jurisdictions.

Only four local governments in Los Angeles County are not signatory to the California Master Mutual Aid Agreement, but all four contract with the County of Los Angeles for essential service. Thus, the County provides and receives mutual aid on their behalf. Therefore, it may be assumed that for practical purposes all local governments in Los Angeles County are signatories to the agreement.

COORDINATION

The California Emergency Services Act makes mandatory the establishment of County operational areas for war emergencies, which are described as links "in the system of communications and coordination between the State's emergency operating centers and the operating centers of the political subdivisions comprising the operational area(s)." It is further stated in the Act that county operational areas may be utilized in non-war emergencies.

The Los Angeles County Operational Area was organized pursuant to the Act with the Sheriff designated as the individual who is responsible for providing the communications link indicated and providing the necessary operational coordination. The legislative bodies of seventy-five of the seventy-seven cities of Los Angeles County have passed resolutions concurring with this arrangement.

The decision to activate county operational areas, throughout California, in non-war emergencies rests with the local governments concerned. Currently, no agreement or understanding exists among the local governments in Los Angeles County to activate the Los Angeles County Operational Area for emergencies other than war or otherwise to provide for coordination among local governments.

Coordination between and among counties is the responsibility of the State. The California Emergency Services Act and the California Emergency Operations Plan provide for intercounty coordination.

EMERGENCY COMMUNICATIONS

Communications systems are an essential element in the conduct of emergency operations. In the February 9, 1971, earthquake land-line communications again proved to be vulnerable to damage. Because of this it is concluded that radio should be the primary communications system for use in emergencies.

Many radio systems are available for disaster application in Los Angeles County, but primary reliance is placed upon those operating on public-safety channels that are assigned to local governments by the Federal Communications Commission for police and fire departments and for general government use, and to nongovernmental agencies such as schools and private ambulance companies.

The HEAR (Hospital Emergency Administrative Radio) System received its start several years ago when the Federal Communications Commission made several radio frequencies available for hospital use. Many hospitals in Los Angeles County have installed HEAR radio equipment and others are doing so as funds

* Reprinted from Report of the Los Angeles County Earthquake Commission, San Fernando earthquake, February 9, 1971.

for communications equipment become available. Recently, the County Board of Supervisors authorized the Sheriff's Department and the County Fire Department to install radio equipment operating on HEAR frequencies, thus linking county government to the system. The HEAR System is an important contribution to the conduct of emergency operations.

Back-up radio communications are provided by the RACES (Radio Amateur Civil Emergency Services) organization. This is a volunteer organization composed of amateur radio operators who operate their own equipment, which includes mobile and portable units. The emergency potential of the RACES organizations, with hundreds of registered amateur operators in Los Angeles County, is great. However, the operators must be organized, trained and motivated. The Sheriff's Department has undertaken the task of organizing RACES on a countywide basis and to provide essential training.

However, it is abundantly clear that any radio system that is based partially upon land lines and relying on commercial power is very vulnerable. Emergency power is essential, and such facilities must be installed to resist severe shaking without loss of function. Redundant systems also should be considered so that a single case of damage would not prevent communicating entirely.

Many local, State and Federal radio systems are available. The problem is to harness these systems for emergency use by providing the necessary interconnect stations. The means to do so can be determined only by a detailed study of available systems and the equipment required to provide linkage between systems. This should be undertaken and a countywide communications plan prepared.

DISASTER DECLARATIONS

The County Board of Supervisors declared a local emergency promptly upon convening on the morning of February 9, 1971. The Chairman of the Board also contacted the Governor and recommended that the Governor (1) declare a state of emergency and (2) recommend to the President that he declare Los Angeles County a major disaster area. Both the Governor and the President acted within hours. The latter's declaration of Los Angeles County as a major disaster area paved the way for substantial Federal assistance.

JURISDICTIONS INVOLVED

Three local governments—the City of San Fernando, the City of Los Angeles, and the County of Los Angeles—bore the brunt of the San Fernando earthquake. Much of the severe damage occurred along the Los Angeles County-City boundary in the northern part of the San Fernando Valley. As a result, there was an unusual commingling of emergency operations. For example, Olive View Hospital and San Fernando Juvenile Hall, both heavily damaged, are County facilities that are located in the City of Los Angeles. The San Fernando Veterans Hospital is a Federal facility located in County (unincorporated) territory and is almost entirely surrounded by the City of Los Angeles. The heavily damaged segment of the State highway system lies both in the County and City of Los Angeles. The San Fernando Dams and Van Norman Lakes lie wholly in the City of Los Angeles.

LAW ENFORCEMENT OPERATIONS

The evacuation of persons living below the San Fernando Dam was handled effectively by the Los Angeles Police Department. In accordance with plans previously prepared, approximately 80,000 people were evacuated from the threatened area. It required four days to drain the reservoir to a level safe enough to permit the evacuees to return to their homes.

Following the report that a building had collapsed at the San Fernando Veterans Administration Hospital, City of Los Angeles Fire and Police Department units were dispatched immediately even though it was a County operational responsibility. The City units initiated rescue operations and continued them until an orderly transfer could be made to County units.

FIRE AND RESCUE OPERATIONS

Large earthquakes may cause destructive fires as occurred in Tokyo in 1923 and in San Francisco in 1906. Some fires did occur in San Fernando Valley but, fortunately, not to the extent of a major threat. The City of Los Angeles on February 9 reported 436 fire calls as compared to a February daily average of seventy-three. There were actually 128 fires, of which two were major. The City of San Fernando had only three fire calls directly attributable to the earthquake and, of these, only one was a structural fire, which was minor. The County of Los Angeles responded to thirty-two fire calls.

Rescue calls were similarly increased. The City of Los Angeles received 457 on February 9 as compared to a February daily average of 276. The City of San Fernando Fire Department responded to 147 rescue calls and the County to six. Fortunately, most of these were of a minor nature. The exception was the San Fernando Veterans Hospital, where round-the-clock heavy-rescue operations were conducted over a period of four days.

HELICOPTER RECONNAISSANCE

The City of Los Angeles Police and Fire Departments, the Sheriff's Department and County Fire Department dispatched helicopter reconnaissance flights to the general earthquake area shortly after the initial shock. Their value in a damage-survey role was amply demonstrated. An even greater value would have been realized had this information been made available to other interested departments and agencies.

BUILDING INSPECTIONS

The damage caused to structures throughout the earthquake area imposed an immediate and heavy demand for building inspectors. The City of Los Angeles diverted practically its entire force of about 250 building inspectors to the stricken area. For the first two weeks this force worked evenings and weekends in addition to regular working hours. In the month following the earthquake 27,160 structures were inspected in Los Angeles City territory.

The County Engineer assigned a team of forty building inspectors to survey structures immediately after the earthquake occurred. Approximately 4,000 buildings were inspected in unincorporated County territory during the first four weeks after the earthquake.

The City of San Fernando, with only one building inspector and one electrical inspector, was faced with an inspection task far exceeding its capabilities. The State Division of Housing and Community Development was contacted and provided eight inspectors for four days. The State Office of General Services also was contacted and provided two inspectors through the Office of Architecture and Construction for a combined time-total of three man-months. The City of San Fernando hired one additional inspector on a temporary basis. In the weeks following the earthquake every one of the 5,200 dwellings in the City of San Fernando was inspected.

TRAFFIC DISRUPTION

Traffic was seriously disrupted on Interstate 5 and State Highway 14, which are main traffic arteries to and from the north and northwest. By early evening of February 9, one lane of traffic was established in each direction on State Highway 14; by February 19 two lanes of traffic were established in each direction on Interstate 5. Pending emergency repair, alternate routes were established that passed the heavily damaged area.

In this particular instance, serious consequences did not result from disruption of these two main highways. However, the earthquake did demonstrate the vulnerability of a metropolitan area that is heavily dependent upon its highway system. An earthquake of greater magnitude could cause extensive and prolonged traffic interruption and isolate large areas of the County.

RESTORATION OF UTILITIES

All utilities in the earthquake area were disrupted. Restoration of service, however, was surprisingly quick considering the damage sustained. Municipal water was restored to most of the area in four to five days and to all areas in eleven days. Power was restored in two days to all parts with the exception of the evacuated area below San Fernando Dam, which had power again by the evening of February 12 when residents were permitted to return to their homes.

Gas service was restored to most customers in five days and to the remainder in eleven days. The telephone system was back in service for 8,000 customers in six days, with complete restoration of service in twenty-one days. Repair of sewer lines was a tedious and time-consuming task because of the difficulty in locating the many breaks; nevertheless, emergency repairs were virtually completed within two weeks.

WATER SUPPLY

Breaks in water lines throughout the disaster area caused an acute shortage of water for basic needs. A local brewing company responded to the emergency by supplying pure water from its brewery in Van Nuys. Twenty-eight 4,000-gallon tanks were delivered to various locations filled—and refilled—with water that had been boiled, chilled and rechlorinated. More than 400,000 gallons of water was distributed during the period that water was in short supply in the earthquake area.

MEDICAL CARE

Approximately 2,400 people sustained earthquake-related injuries, of which the great majority were relatively minor.

One of the most serious aspects of the earthquake was the fact that four hospitals—Olive View Hospital, San Fernando Veterans Hospital, Pacoima Memorial Lutheran Hospital and Holy Cross Hospital—were so severely damaged that they could no longer function. The effect was to remove from use a total of 1,553 beds, which necessitated the transfer of about that many patients.

RED CROSS

Ministering to the needs of disaster victims was a major task. The American Red Cross carried most of the load. The Los Angeles Chapter office was activated within forty-five minutes following the earthquake, and key personnel and volunteers were alerted. Within hours six Red Cross shelters were established in schools of the Los Angeles City Unified School District; in the next few days, as the need arose, four additional shelters were activated. A total of 175,000 meals was served, plus 52,000 sandwiches. Additionally, eight mobile canteens were operated. The cost of the mass-feeding operations was about $125,000. Ten relief centers were established to meet the emergency needs of people for such items as rent, food, clothing, medical and nursing care, and minor household needs.

The Red Cross assisted over 11,000 families at a cost in excess of $1,148,000. The Salvation Army and other charitable organizations also made notable contributions to the relief of disaster victims.

DISASTER ASSISTANCE CENTERS

The San Fernando Earthquake, as might be expected, created a variety of human needs: food, clothing, shelter, medical attention, debris removal, disaster loans and others. Assistance was available for ministering to all of these needs from the American Red Cross and various Federal and local government agencies. In order to provide on-the-spot help the three jurisdictions most seriously involved—the County and the cities of Los Angeles and San Fernando—acting jointly, established assistance centers in the stricken area. These centers, well-publicized and staffed with representatives of the various disaster relief agencies, greatly facilitated rendering of assistance to individuals.

MUTUAL AID

Although this earthquake ranks as one of California's major disasters, recourse to the provisions of the California Master Mutual Aid Agreement was limited. The emergency operating resources of the County and City of Los Angeles were not unduly extended. The City of San Fernando, with less extensive means and lying wholly within the earthquake area, felt the strain upon its resources far more than the County and City of Los Angeles. Mutual aid was provided primarily by the State in assigning building inspectors to the area.

Assistance from other jurisdictions was available and would have been provided promptly upon request. In the hours that followed the earthquake assistance was offered by unaffected local governments both from within and without Los Angeles County.

NEED FOR BETTER TEAMWORK

The Commission's review of operations, conducted by local government departments following the earthquake, revealed certain weaknesses. These did not seriously impair the performance of the various governmental agencies involved in this particular event because operational requirements were well within the capabilities of local agencies. However, in a disaster of greater proportions the inadequacies noted would have been magnified and would have resulted in wasted motion and uneconomical utilization of available resources, and could have caused a chaotic situation.

Most apparent was the fact that the local, State and Federal agencies that were involved conducted their emergency activities independently of each other at a time when team effort or coordination would have been mutually helpful. This was evidenced by the almost total lack of communication among the agencies. Some agencies received reports from the field, mostly from mobile units, within minutes after the earthquake occurred. Other agencies dispatched helicopters to ascertain the extent of damage. Information obtained from these sources was not passed to other agencies of the same jurisdiction or to interested agencies of other jurisdictions. The result was that information of the full extent of the disaster was slow to reach some responsible agency heads.

The situation at the San Fernando Veterans Hospital was not known until 7:23 a.m., when City of Los Angeles Fire Department personnel on a helicopter reconnaissance flight spotted the heavy damage. Units of the City of Los Angeles Fire Department were dispatched promptly to the scene. The County Fire Department, which has responsibility for fire-fighting and rescue operations in this unincorporated area, did not become aware of the situation until 9:05 a.m., and the Sheriff's Department was not informed of it until 10:30 a.m.

The District Engineer of the United States Army Corps of Engineers reported that his emergency operating center was opened shortly after 7 a.m., February 9, and that he arrived there at 7:15 a.m. About 7:45 a.m. he witnessed, on commercial television, the damage to the San Fernando Veterans Administration Hospital and proceeded there by helicopter, arriving shortly after 9 a.m. He stressed to the Commission the need for a tie-in between the Federal radio network and local police and fire department networks.

The general manager of the Department of Building and Safety, City of Los Angeles, reported that his department was not able to ascertain the areas of heaviest damage until midafternoon. He stressed the need for a central fact-finding center in such situations.

The State Division of Highways district office in Los Angeles received reports of severe damage to the State highway system within a few minutes after the event as did the Los Angeles Zone V office of the California Highway Patrol. Emergency traffic-control measures were initiated promptly.

RECOMMENDATIONS

Within the current state of scientific knowledge, it is not possible to predict the time of occurrence, the location or the strength of future earthquakes. However, on the basis of past experience, strong shaking can be expected throughout the metropolitan Los Angeles area in the future as in the past. Therefore, it is most important that the experience gained from the San Fernando earthquake be translated into usable and effective plans and measures for future earthquakes. The Commission believes that the implementation of the following recommendations will improve substantially the ability of jurisdictions in Los Angeles County to cope with a major earthquake disaster.

Local governments should establish emergency operating centers for the collection and dissemination of information and for the direction and coordination of emergency operations in the event of a major disaster. Integral to the emergency operating centers should be adequate communications, including interconnect stations to ensure emergency utilization of all major communications systems within the jurisdiction.

Local-government communications systems should not be dependent solely upon land lines and commercial power. Communications systems and emergency power installations should be designed and constructed so that they can survive very strong shaking without loss of function.

Local-government officials should evaluate and update their plans, procedures and preparedness measures for coping with the effects of damaging earthquakes in the light of the experience derived from the February 9, 1971, event.

Particular attention should be given to: (1) establishing plans for coping with major conflagrations coincident with widespread disruption of the normal water supply and adverse meteorological conditions as may occur following a major earthquake; (2) the utilization of helicopters and fixed-wing aircraft for disaster reconnaissance and for the prompt dissemination of emergency information obtained therefrom to interested agencies; (3) the training of personnel for heavy-rescue operations; (4) the conducting of periodic earthquake exercises for training of staff personnel; (5) preparing plans for meeting a heavy demand for building inspectors to inspect damaged structures; (6) preparing plans for the evacuation of hospitals, penal and correctional institutions; (7) providing the means of supplying and distributing potable water when the normal water supply is disrupted; (8) preparing detailed plans for the establishing of disaster assistance centers to serve individuals in need of help, and (9) the preparation of contingency plans for the rapid evacuation of persons living below dams.

County and city governments in Los Angeles County should take steps to provide for the activation of the Los Angeles County Operational Area organization for major non-war disasters when the situation indicates that interjurisdictional coordination of emergency operations is advisable.

The County of Los Angeles, having responsibility for countywide coordination of emergency operations in war emergencies and as agreed upon for non-war emergencies, should establish an emergency operating center to function on a countywide as well as jurisdictional basis. This center must have radio links to key local, State and Federal radio systems. The nucleus of the emergency operating center should be operational on a day-to-day basis and be capable of being expanded quickly to full-scale operations following the onset of major disasters.

A study of the communications systems in Los Angeles County that would be available for emergency utilization should be undertaken with the object of determining communications deficiencies. A countywide communications plan also should be prepared.

A countywide emergency transportation plan should be established to ensure movement of essential supplies, equipment and personnel to areas of need in Los Angeles County when normal routes are disrupted.

CHAPTER 32

Disaster Response–Assistance to Individuals[1]

by Frederic I. Ross [2]

6:00:40 a.m., February 9, 1971—Thousands of Los Angeles Basin citizens were rudely awakened to "disaster". Within minutes, emergency agencies were in action, massing and deploying resources to relieve the human misery that inevitably must follow.

By 6:40 a.m., Los Angeles Police Department command posts were strategically located throughout the city's affected area, making situational reports to the Police Department's Central Emergency Control Center, which was functioning by 6:30 a.m. These operations began in accordance with a well-developed LAPD emergency plan.

By 7:00 a.m., the Control Center had developed a fairly composite assessment of the over-all emergency situation within the city. Of top priority was a possible threat to 80,000 persons living below San Fernando Dam. Acting on a Los Angeles Department of Water and Power report of potential dam failure, received shortly after 7 a.m., the LAPD put into effect a planned evacuation operation. Evacuation area perimeters were established from maps which had been prepared in anticipation of such need. By 7:30 a.m., LAPD field commanders had begun evacuation operations.

Almost immediately, on notification of potential dam failure, the LAPD advised an already-girding local American National Red Cross (ANRC) Chapter of a need for shelters to receive evacuees.

A few minutes after 8 a.m., the first Red Cross shelter was in operation. By 9:10 a.m., four more centers were open and providing for the first few hundred confused and dazed evacuees, whose numbers would, before the night, swell to over 6000.

The Red Cross response was one of professionally planned precision. By previous arrangement with school districts, specified schools, on notification from the Red Cross, were opened as shelters. Professional and volunteer Red Cross personnel and members of the Los Angeles County Department of Public Social Services speedily moved into the designated shelters and systematically put tried and tested emergency procedures into effect. Food stores were laid in; cots and bedding were provided; medical facilities were set up; and arrangements were made for satisfaction of other personal needs as they arose.

Through the ensuing week, the Red Cross moved quickly to establish or participate in assistance centers as new geographical areas of need became apparent.

[1] Manuscript submitted for publication June 30, 1971.

[2] At time of earthquake, State Office of Emergency Services, Sacramento.

Before 8 a.m. of February 9, 1971, the Los Angeles Area (U.S. Department of Agriculture) Food and Nutrition representative had informed the Red Cross of surplus food warehouse locations and, under singular statutory authority, approved emergency use of the food stores.

Within 30 minutes of the first temblor, Gardner Davis, Office of Emergency Services Field Representative, had activated the Region I Emergency Operations Center and established contact with the Los Angeles Police Department, the Los Angeles County Sheriff's Office, and other emergency response agencies. As information became available to the Region I office, it was relayed to the Sacramento Office of Emergency Services.

From 6 a.m. until 8:30 a.m., reports were disarmingly void of significant havoc. There were reports of a damaged but apparently safe San Fernando Dam, of broken glass, scattered fires, and ruptured gas, electric, and water lines; but most situations appeared under control. Then, in the ensuing hour, the spectre of disaster became manifest. News of casualties under broken buildings at the Olive View Hospital was followed shortly by word of a devastated Veterans Administration Hospital. Then came varying reports of imminent dam rupture, of collapsed highway overpasses, and of extensive private home damage. San Fernando City broke an almost 3-hour silence with an urgent plea for assistance.*

At the Office of Emergency Services in Sacramento, an almost routine morning erupted into positive action. Intelligence was consolidated from telephone, television, teletype, and radio reports. Facts, figures, and status of casualties and destruction were compiled and rushed by Deputy Director R. Dale DeStaffany to the Office of the Governor, where the Chief Executive evaluated the situation and by 10:30 a.m., had proclaimed a "state of emergency" in Los Angeles County and directed full State agency participation in mitigation and recovery operations.

The Governor then relayed a request to the President of the United States for Federal assistance. By 1:30 p.m., the President had declared a "major disaster" in the affected area and directed the full application of Federal resources to supplement State and local disaster response.

*Notable among agencies providing desperately needed drinking water to San Fernando City and other affected areas were Jos. Schlitz Brewing Co. and Arrowhead Puritas Water. These companies delivered and strategically situated 327,000 gallons and over 50,000 gallons of pure water, respectively. Sparklets and Coca Cola also provided water, but the quantities are not known. The California National Guard provided and maintained 33 600-gallon trailers of drinking water at affected schools.

Even prior to the Governor's proclamation, key representatives from various State agencies began to assemble at the Region I EOC. Geological field investigations by the State Division of Mines and Geology had begun by 8:00 a.m. By 11 a.m., the Division of Highways, Department of Water Resources, Office of Architecture and Construction, Military Department, Department of Justice, Highway Patrol, Department of Public Health, and the Department of Housing and Community Development were represented at the EOC. Almost simultaneously, the Federal Office of Emergency Preparedness, in anticipation of a Presidential Declaration, activated a field office within the Region I EOC.

At approximately 2 p.m., the Governor was in Los Angeles receiving a briefing from Michael Colby, Office of Emergency Services Regional Manager, and representatives from other State and local agencies. Within three hours thereafter, John McCoy, OES Director, and Gordon Larkin, State Coordinating Officer, were on their way to the disaster area.

On the morning of February 10, 1971, representatives from Federal, State, and local agencies joined with the Federal and State coordinating officers to map a plan of cooperative emergency action.

Of primary concern was the prompt relief of human suffering and reduction of hazard. All day of the tenth was occupied with these immediate objectives. On the eleventh of February, attention was directed to providing the affected populace with post-emergency assistance. This included temporary housing, loans for home repair and replacement, and unemployment benefits.

The Federal Department of Housing and Urban Development (HUD) was designated by OEP to provide temporary housing and rent and mortgage-payment assistance to disaster victims. It was determined that HUD would make its resources available through the Los Angeles City Housing Authority and the Los Angeles County Urban Affairs Department, respectively.

Under the Federal Disaster Relief Act, a homeowner whose home was made unhabitable by the earthquake was authorized up to a year's free rental in suitable temporary housing. A person renting a home that was made unhabitable by the earthquake was provided the same service if his over-all cost of living was increased significantly through having to change residence. HUD was also authorized to assume either rent or mortgage payments for up to 12 months for those persons with notice of eviction or foreclosure who were unable to meet payments because of earthquake-induced financial hardship.

Financial assistance for repair and replacement of homes, furniture, and other designated personal effects was provided by the Federal Small Business Administration (SBA) in the form of low-interest long-term loans. These loans were made available to qualified applicants at a 5⅛ percent interest rate,* a 30-year

Table 1. Disaster assistance provided by the U.S. Department of Housing and Urban Development under the Federal Disaster Relief Act (PL 91-606) through June 15, 1971.

TEMPORARY HOUSING (Section 226a)		MORTGAGE AND RENTAL ASSISTANCE (Section 226b)	
Applications	*No.*	*Applications**	*No.*
Received	1,987	Received	140
Satisfied	1,150	Approved for payment	50
Disapproved (ineligible)	231	Disapproved (ineligible)	13
Withdrawn	40	Withdrawn	3
In process	566	In process	74

* These applications resulted from HUD's processing 6,089 inquiries and counselling 2,744 prospective applicants.

term, and with a $2500 forgiveness feature. Under the forgiveness clause, after the first $500 of a loan is repaid, the remainder of the amount owed is reduced by as much as $2500. Thus, if a person borrows $5000, he has, after repaying $500 of the amount, only $2000 remaining to pay. On these terms, an individual could borrow up to $50,000 for repair or replacement of his disaster-damaged home. A person could also borrow up to $10,000 under the same terms for repair or replacement of personal property damaged or lost in the quake. However, the sum of a home loan and a personal property loan to the same individual cannot exceed $55,000.

Such loans may, however, only apply to losses, or parts of losses, which are not covered by insurance or other means. Thus, if half of a $10,000 loss were covered by insurance or, perhaps, by a Red Cross grant, then the borrower could only get an SBA loan for the remaining $5000.

The SBA may also defer payment of principal and/or interest on such loans, if such deferment is requested within the first three years of the loan term. In the San Fernando Valley disaster, a 5-month deferral of both principal and interest was automatically granted. A disaster-damaged home could also be refinanced for up to the same amount and under the same terms as for a new loan, except that to be eligible, damage to the home must exceed 50 percent of its fair market value.

Table 2. Status of Small Business Administration's assistance as of June 15, 1971.

Applications	*Home Loans* No.	*Home Loans* Value	*Business Loans* No.	*Business Loans* Value
Accepted	15,439	$59,831,121	1,082	$30,863,102
Approved	13,474	$50,241,681	677	$14,918,854
Satisfied	10,482	$28,451,467	262	$3,250,805
Withdrawn	31	$207,990	6	$68,700

Under PL 91-606, both the U.S. Farmers Home Administration (FAHA) and the Federal Housing Administration (FHA) could refinance at 5⅛ percent

* This rate may vary among different time periods because it is based on the current average market yield on outstanding U. S. marketable obligations.

interest existing loans made or insured by them. FHA could also suspend payments of interest and/or principal for up to five years on loans they insured. FAHA may extend the term of a refinanced FAHA loan up to 40 years. As with the SBA, the FAHA may also forgive up to $2500 on any disaster loan they make under PL 91-606, and they may defer payment of principal and/or interest if a request for such deferment is made within the first three years of the loan term. As of June 25, 1971, there were no known applicants for FHA or FAHA refinancing or payment suspension.

The U.S. Veterans Administration has authority to excuse part or all of a VA-insured mortgage on property damaged or destroyed by a disaster. This authority, which is exercised on an individual basis, may apply to a house being purchased under veterans' entitlement or to an administrator-acquired house (repossession) used as security for a VA loan. As of June 25, 1971, the VA had excused the remaining debt on three "repossessions" that were destroyed by the quake.

The California Department of Veterans Affairs (DVA), under Article 3.7, Section 989 of the Military and Veterans Code, is authorized to indemnify disaster-incurred home losses suffered by persons purchasing homes under the Cal-Vet program. In the San Fernando Valley disaster, the Department of Veterans Affairs filed over 600 claims under the above section; and they estimated a total disbursement of $500,000 will result from these claims.

On the scene to provide unemployment compensation for those whose employment was curtailed as a result of the temblor was the California Department of Human Resources Development (HRD). They not only processed claims under State law, but administered the Federal program of the U.S. Secretary of Labor. The Federal program provided assistance to individuals rendered unemployed by the quake but who were ineligible for State unemployment benefits. State benefits range from $50 to $65 per week for 26 weeks (and longer under certain circumstances). Federal benefits came to $55 a week for the same time period. Of the latter, HRD processed over 4500 claims. The number of claims processed wholly under the State program could not be ascertained because disaster claims were indistinguishable from those routinely processed.

Time and regulatory gaps in government assistance were effectively filled by the Red Cross, with total outlay of approximately $1½ million, broken down in the following areas:

Assistance	*Numbers*
Shelters	10
People sheltered	17,000
Meals fed	66,500
Mass feeding locations	2
Meals fed	108,600
Mobile feeding (trucks)	8
Sandwiches	18,000
Orange drink (cartons)	12,000
Water (gallons)	7,200
Assistance centers	10
Sandwiches	52,000
TOTALS:	
Facilities	30
People sheltered	17,000
Sandwiches	70,000
Meals fed	175,100
Orange drink (cartons)	12,000
Water (gallons)	7,200

A total of 11,867 people registered for and received the following totals in assistance from the Red Cross:

Type assistance	*Dollar amount*	
Clothing and maintenance	$550,000	
Building and repairs (including assistance in rental and mortgage payments and in qualifying for loans)	60,000	
Furniture	450,000	
Medical and nursing	40,000	
Occupational supplies and equipment	4,500	
TOTAL:	$1,104,500	
ADD: Cost of mass care (from preceding chart)	150,000	
Overhead	245,500	
GRAND TOTAL:		$1,500,000

As a hypothetical case in assistance to a home owner, let us assume an individual was purchasing a $25,000 home (including $5000 raw land value) which sustained $15,000 (75 percent) damage from the earthquake and is now unhabitable. Here is a man and his wife, their house broken and askew on its foundation, their children hungry and crying, perhaps one or more of them suffering injury—What are they to do? Where are they to go?

The first move is to the Red Cross, which is normally the first on the scene with emergency shelter, food, clothing, medical aid, and counselling. After seeing to the family's immediate needs, the Red Cross counsellor will assess the family's straits and refer the homeowner to the appropriate government agency or agencies for recovery assistance. If needed assistance is not reasonably available from other agencies, the ANRC may provide it from its resources.

In this instance, it's probable that the Red Cross is located in one of six assistance centers, set up to provide easy access to a broad grouping of assistance agencies. Other agencies represented in the centers may include HUD, SBA, HRD, and other Federal, State, and local offices which may have resources available for individual assistance. Such centers were conceived as a single convenient point to provide disaster victims with as immediate and complete recovery assistance as reasonably possible. Thus, our hypothetical case is simply referred to another desk within the same building.

First, he must find temporary housing while arranging financing and awaiting repair of his home. For this, he will be referred to the local agency administering the HUD temporary housing and assistance program. In the San Fernando earthquake, these were the Los Angeles Housing Authority representing the City and the Urban Affairs Department representing Los Angeles County. Here, with minimal processing, he will be provided, rent-free for up to 12 months, a temporary home of proper size and quality to house the family. He has the option of selecting a home

Table 3. Summary of agencies providing assistance in the San Fernando earthquake disaster.

Type of assistance	*ANRC*	*HUD (FHA)*	*USDA and FAHA*	*SBA*	*VA*	*HRD and Labor*	*DVA*
GRANTS (money or purchase order)	1						
Food	1						
Medical	1						
Personal property	1–16						
Home repair or replacement	1	18					
Occupational equipment and material							
Temporary housing	1–3						
UNEMPLOYMENT COMPENSATION						19	
MORTGAGE AND RENTAL PAYMENT ASSISTANCE		2					
HOME LOSS INDEMNITY							20
TEMPORARY HOUSING (rent-free)		4–23					
HOME LOANS (old)		8–9	6–10		5		
HOME LOANS (refinancing, low-interest)		8–9	7–10–13–17	7–13–17			
HOME LOANS (new, low-interest)			7–13–14	7–11–13–14			
PERSONAL PROPERTY LOANS				15			

1 Provided on basis of need, not loss, when other sources of assistance are unavailable or inadequate.
2 Will pay rental or home-loan installments when individual has financial hardship from a major disaster and has received written notice of eviction or foreclosure.
3 Up to 1 week.
4 Up to 12 months.
5 Obligation may be excused or otherwise adjusted as warranted by facts in each case.
6 May adjust and readjust payment schedules on Rural Electrification Act loans.
7 May defer payments (in part or in whole) if requested within 3 years from outset of loan term.
8 May defer payments for up to 5 years.
9 May extend loan term up to 5 years.
10 May extend loan term to maximum of 40 years.
11 Maximum term of 30 years.
12 Maximum term of 40 years.
13 May cancel up to $2500 of principal in excess of $500.
14 Up to $50,000.
15 Up to $10,000 (home loan + personal property loan cannot exceed $55,000).
16 No prescribed ceiling.
17 If damage exceeds 50 percent of value.
18 When eligible as urban renewal project.
19 $50–$65 a week for 26 weeks.
20 If buying home under Cal-Vet program.
21 At 3 percent interest (under urban renewal project).
22 On homes held as security for a VA-made or -insured loan.
23 When home made unhabitable by a disaster.

from available listings or going out on his own and finding a home which meets the prescribed standards and price ceiling.

After arranging temporary housing, he must now tackle financial arrangements for satisfying his original mortgage and effecting necessary repairs to his damaged home.

Let us assume he had a $10,000 equity in the home, with his loan being paid off at 7 percent interest rate, over a 30-year term. Thus, he is not only faced with a $15,000 repair cost, but a loan balance of $15,000, with monthly payments of $222 (including taxes and insurance). Under these circumstances, he could refinance his original loan and gain a new loan for home repair, both at 5⅛ precent interest; and, since his home damage was in excess of 50 percent of fair value, he could obtain both loans, and consolidate them, through the Small Business Administration. If damage had been less than 50 percent of fair value, and his home loan insured by either FHA or FAHA, he could still have had his original loan refinanced through these agencies.

Now, a combined loan of $30,000 (less $2,500 forgiveness) at 5⅛ percent interest rate would result in monthly payments of $206, sixteen dollars less than his original payments, but with another full 30 years for repayment. Now, let's make his situation even worse. Let's assume that his wife's job and resulting supplemental income were eliminated because of the quake. He now finds the total family net income is not sufficient for him to qualify for the needed loan. His net income now will qualify him for only a $20,000 loan. At this point, let's say that he is able to provide $2,500 from personal resources to reduce the loan need to $25,000—still beyond his means; and worse yet, he has received notice of foreclosure on his original loan. Here, he can return to HUD, who may, under such circumstances, make his mortgage payments for him for up to 12 months. Then, he can turn again to the Red Cross, who may provide the homeowner with an outright grant of the $5,000 needed to qualify him for the SBA loan. He now negotiates a $20,000 loan, with monthly payments of only $164. If his circumstances are relatively insecure and he finds making the above payments may incur a hardship at this critical point in time, the SBA may defer monthly payments until he is in a better financial situation.

Had our disaster victim's original home loan been insured or made by the U.S. Veterans Administration and his ability to repay significantly impaired, he may have had all or part of his loan balance cancelled. Similarly, had his home been security for a loan made by the VA in the sale of administrator-acquired properties (repossessions), the indebtedness could also be excused on an individual basis. And, if he had been so fortunate as to have acquired his home under the California Department of Veterans Affairs "Cal-Vet" program, his home could have been repaired or replaced at no cost to him.

On the other hand, in a perhaps less-than-ethical approach, our hypothetical disaster victim could simply default on his original loan and obligate himself only with the new low-interest loan. This was, in fact, the route taken by some in the San Fernando Valley disaster.

In the San Fernando earthquake of February 9, 1971, there were many noble and generous individuals and agencies who contributed immeasurably to the relief and recovery of stricken citizens. To appropriately recognize, in this writing, all these contributions would require many times the space allowed in this bulletin. Therefore, except for necessary "stage-setting" developments, this article has been restricted to the few major sources of recovery assistance to individuals. The objective has been to delineate and clarify assistance offered by these agencies to enlighten the reader on advances being made in organized and planned disaster relief.

Assistance provided by agencies discussed herein is summarized in table 3, which contains general information as it relates to the San Fernando earthquake. For details concerning eligibility, qualifications, limitations, and procedures, you should contact the providing agency.

Section 5

Minimizing Losses

CHAPTER 33

Legislative and Administrative Earthquake-Protective Measures by State Government in California

by Gordon B. Oakeshott [1] and Wesley G. Bruer [2]

HISTORY OF OFFICIAL STATE INVOLVEMENT

The San Fernando earthquake produced a wealth of instrumental data, far more than ever obtained from any previous earthquake. It is already one of the most thoroughly studied earthquakes in history, and studies are continuing. In addition to the voluminous earth-science data generated by this event, more information is already available on loss of life, injuries, and property damage than for any other American earthquake. This mass of data has advanced—and will continue to advance—the body of knowledge in all fields necessary to reduce losses effectively in future seismic events.

Conclusions and recommendations have followed every earthquake, increasing in number and detail with successive earthquakes. A century ago, after the great Owens Valley earthquake of 1872, the editor of the *Inyo Independent* concluded that "severe and appalling as this great convulsion of the earth unquestionably was, it is a settled conviction with all here that not a person would have been killed or hurt had their houses all been made of wood". He then made the recommendation "... to forever eschew adobe, brick, and stone in buildings" (Oakeshott *et al.*, 1972). The single-story, wood-frame house has proved its worth in many subsequent earthquakes in California. (See, for example, Steinbrugge in this Bulletin). After San Francisco 1906, the California Earthquake Commission (Lawson *et al.*, 1908) said: "It is evident that much of the damage to houses, as well as to their contents, could be avoided by judicious construction. The disadvantages of certain classes of structure should be acknowledged and search made for more successful styles. Houses practically earthquake-proof can be built easily and cheaply." Today's structural engineers confirm that man-built structures can be made highly earthquake-resistant at an added cost of a few percent of the total cost of construction if earthquake-resistant measures are incorporated in the design.

What is being done to reduce earthquake risk in California? The San Fernando earthquake, unlike so many previous California earthquakes, continues to receive great attention from all levels of government, from universities, and from the private sector, more than two years after the event. It may have provided the impetus for efforts which will lead to a truly significant improvement in seismic safety for the citizens of the state. While the programs of other entities are no less important, the seismic safety activities of the State of California are the primary subject of this report.

Perhaps the first *official* evidence of concern of the State of California about earthquakes was reprinted in full in the 8th Annual Report of the State Mineralogist (since 1961, again "State Geologist") of State Geologist J. D. Whitney's two papers on the Owens Valley earthquake of 1872, originally published in the *Overland Monthly* of September and October of 1872. It is interesting that the earthquake of 1872 was felt in Sacramento and that the new capitol was damaged when an iron column was broken.

The first major step in State-of-California participation in earthquake investigations was taken by Governor George C. Pardee when, three days after the great San Francisco earthquake of April 18, 1906, he appointed the State Earthquake Investigation Commission. The Commission was chaired by Professor A. C. Lawson, famous University of California geologist, and manned by greats of the time, including J. C. Branner of Stanford's Geology Department, G. K. Gilbert of the U.S. Geological Survey, H. F. Reid, professor of geology at Johns Hopkins, and several noted astronomers. Following the earthquake, the Carnegie Institution of Washington published the monumental *Report of the State Earthquake Investigation Commission** which remains one of the greatest accounts of an earthquake ever published.

Nineteen thirty-three was a year of disaster, with California's third most costly earthquake occurring in the Long Beach area on March 10. Scandalous structural failure of dozens of school buildings caused the Legislature to pass the "Field Act". This Act requires the State Office of Architecture and Construction to set up rules and regulations concerning earthquake safety in design and construction of school buildings. These regulations are now included in Title 21 and Title 24 of the California Administrative Code. The law is not retroactive, so California's public school buildings are now categorized as *approved* or *unapproved.* The Act has been highly successful in reducing damage in subsequent earthquakes. The problem of the continued use of the older *unapproved* school buildings is being attacked by the new revision of the

[1] California Division of Mines and Geology at time of earthquake; now Special Lecturer in Geology, California State University at Sacramento.

[2] California Division of Mines and Geology at time of earthquake; now private consultant, Sacramento.

* Reprinted 1969 and available from the Carnegie Institution, Washington, D.C., for $12.50.

Garrison Act requiring that such buildings be brought up to earthquake-resistive standards by June 30, 1975, or their use discontinued.

July 21, 1952, is a date to remember in California earthquake history. The major, magnitude 7.7 Arvin-Tehachapi earthquake caused the loss of 14 lives and $60 million in property at the same time that it confirmed the successful application of the Field Act in maintaining a low level of damage to schools. California Division of Mines Bulletin 171, *Earthquakes in Kern County during 1952*, firmly established earthquake investigation and publication as a proper activity of the California Division of Mines and launched the Division on an accelerating program of earthquake investigation and publication.

CALIFORNIA LEGISLATURE'S JOINT COMMITTEE ON SEISMIC SAFETY

Senate Concurrent Resolution No. 128—Relating to a Joint Committee on Seismic Safety—was filed with the Secretary of State August 25, 1969. The Joint Committee on Seismic Safety thus set up consists of four members of the State Senate plus four members of the Assembly; the Committee is advised by five Advisory Groups, each made up of 14 or 15 authorities in the field. The Joint Committee "shall file a final report with the Legislature not later than June 30, 1974". . . . "The final report shall contain:

a) The results of the detailed study made by the Committee.
b) A plan for continuous revision of the study as new information is obtained.
c) A plan to minimize the probable loss of life and property and to minimize the disruption of the local economy should an earthquake disaster occur.
d) A plan for appropriate and effective response to the immediate problems arising after an earthquake disaster.
e) Such other information and recommendations as the committee deems desirable."

The Joint Committee is chaired by Senator Alfred E. Alquist of San Jose. The Committee is assisted by five technical advisory groups in the fields of Engineering Considerations and Earthquake Sciences, Governmental Organization and Performance, Disaster Preparedness, Land Use Planning, and Post-earthquake Recovery and Redevelopment. Over seventy of California's foremost experts in these fields contribute their time and knowledge while serving on these groups.

The first report of the Seismic Safety Committee (Legislature, 1970) summarized the work of the Advisory Groups to June 30, 1970, including organization, program plan, a summary history of surface faulting and moderate-to-great earthquakes, objectives and work schedules, and a scenario description of effects expected in earthquakes.

The Joint Committee held two hearings during 1970; and the information gained, together with the extensive background material developed by the technical Advisory Groups, enabled legislators of the Joint Committee and other members of the State Legislature to propose a series of bills related to earthquake safety.

The San Fernando earthquake of February 9, 1971, greatly stimulated interest and action concerning earthquakes and their effects in California. On April 27, 1971, enabling legislation (Joint Rules Committee Resolution No. 7) was passed, asking the Chairman of the Joint Committee on Seismic Safety to appoint a "special three-man subcommittee to conduct an in-depth investigation, and report on its findings relevant to events prior to, during, and after the Los Angeles earthquake of February 9, 1971". Complete, in-depth studies by the consultants to the subcommittee were published in July 1972 in the following earthquake subject areas: structural engineering, geological and seismological lessons, dams and soils, city lifelines, land-use planning, disaster preparedness, and government organization and performance.

The Joint Committee continues to promote increased seismic safety through the channels of public information dissemination, public hearings, investigations of past disasters and current standards, introduction of legislation, and development of new proposed policies and programs.

The final report and recommendations of the Joint Committee were presented to the Legislature in 1974.

RECENT LEGISLATION

About 50 pieces of legislation dealing with earthquakes were introduced at the 1971 session of the State Legislature, a large part of it through members of the Joint Committee on Seismic Safety. Perhaps the most far-reaching bills which were passed by the Legislature and signed into law by the Governor were Senate Bills 351 and 691. They require that all general plans of local government consider, among other elements, a seismic safety element consisting of an identification and appraisal of seismic hazards. The Division of Mines and Geology received numerous requests from local government for guidelines in considering this element. In response to the need, the Governor's Earthquake Council prepared *Suggested interim guidelines*. The Division's work in the field of earthquake investigations and its County co-operative programs (see Division of Mines and Geology in the appendix of this paper) are furnishing much information useful to local government in constructing their "seismic safety element".

Senate Bill 1374, also of long-range importance, was approved by the Governor. It directs the Division of Mines and Geology to organize, monitor, purchase and install strong-motion instruments in representative structures and geological environments in the state. The new law provides funds from an assessment of 7¢ on each $1000 of the cost of new building construction. In response, the State Geologist appointed the Strong-Motion Instrumentation Board and the Division began—in July 1972—to purchase and install the first group of ten accelerographs at strategic points throughout the state. The first major goal is to so distribute these strong-motion seismographs as to get a usable record of ground motion wherever in the state a magnitude 6, or greater, earthquake may occur. Such records are of great significance in the design of structures for earthquake safety.

Other legislation which became law in 1971 includes: Senate Bill 386 which allows a refund for taxes paid on stocks of alcoholic beverages damaged by the recent southern California earthquakes; SB 388 which allows a refund for taxes paid on cigarettes damaged by the earthquakes; SB 479 which requires a geologic investigation of prospective additions to schools and proposed school sites; AB 579 which appropriates $1 million for disaster indemnity for veterans; SB 682 requiring the Department of Public Works to conduct and complete an investigation of the geological conditions before ending the reconstruction of highways; and SB 778 requiring building departments of a city or county to maintain plans of the buildings, for which that department has issued permits, to be kept on public record.

In addition, a number of resolutions were passed dealing with a moratorium on mortgage payments (Senate Concurrent Resolution 38), Federal disaster relief funds (Assembly Joint Resolution 33), a Los Angeles earthquake study (Assembly Concurrent Resolution 44), and Senate Concurrent Resolution 84 on the State Capitol earthquake safety. The Los Angeles earthquake study (ACR 44) was completed by the consultants hired by the Hayes subcommittee and published in July 1972 (Legislature, 1972). In accordance with SCR 84, the State Architect evaluated the safety of the West Wing of the Capitol. This old building, built in the late 1860s, was declared unsafe by the State Architect; and he issued a report in July 1972 with estimated costs for different plans for rehabilitation and reconstruction. Meanwhile, the historic old building has been declared out-of-bounds for the groups of school children which have toured the Capitol for many years.

As always, many bills failed to survive the scrutiny of legislative committees, for a variety of reasons. A few, which dealt with such matters of importance as hospital safety, dangerous buildings, and hazardous fault zones, were recast and introduced at the 1972 session of the Legislature.

Over 30 items related to seismic safety were considered at the 1972 session. Early in the 1972 session, Resolution No. 1, cosponsored by Senator Alquist and Assemblyman Hayes, was adopted to establish a Seismic Safety Week and to provide for the placement of historical markers on the fault-line in the San Fernando area. Important 1972 measures passed and signed by the Governor include: SB 519 concerning the structural safety of hospitals in earthquakes; SB 689 making clarifying changes concerning geologic and soils investigations of public school sites; SB 896 which provides that cities and counties shall adopt emergency procedures for evacuation and control of populated areas below dams and that inundation maps be prepared; SB 895 concerning an improved basis for fee collecting in support of the strong-motion instrumentation program; SB 1324 requiring that the State Council on Intergovernmental Relations provide guidelines for the preparation of seismic safety elements now required of all cities and counties; SB 1452 providing that the school bonds intended to replace Field-Act structures need only receive a simple majority of votes to be approved; AB 2329 establishing procedures regarding title to earthquake-disturbed lands; and SB 591 revising the seismic safety element to require appraisal of mudslides, landslides, and slope stability in general. The Governor signed SB 520 which requires the State Geologist to prepare maps, for the use of local government, to designate special studies zones along major active faults. The new law—effective in March 1973—expands the membership of the State Mining and Geology Board and instructs that body to develop policies and criteria necessary. The Division of Mines and Geology began tooling up for this major project in December 1972 in anticipation of the measure's becoming law, and the maps were completed by the end of 1973.

GOVERNOR'S EARTHQUAKE COUNCIL

Prompted by the need for a broadly coordinated approach to the reduction of earthquake hazards, Governor Ronald Reagan appointed the Governor's Earthquake Council in January 1972. The Council is designed to gather all forces concerned with earthquake research and preparedness in California under a single banner. The Council consists of 35 members and 30 alternates representing all levels of government, the universities, the private sector, and the general public.

The Legislature's Joint Committee on Seismic Safety is formally represented on the Council, and a number of Advisory Group members also serve on the Council. This overlapping membership facilitates full cooperation between the Joint Committee and the Council, which is the policy of both organizations.

The Earthquake Council is charged with advising the Governor on measures of any nature that should be undertaken to reduce future earthquake losses in California. These recommendations are not restricted to those for action by State agencies but are to encompass all entities with capabilities in earthquake-related fields.

The organizational meeting of the Governor's Earthquake Council was held on February 28, 1972. Its chairman is a member of the Governor's Cabinet, James G. Stearns, Secretary for Agriculture and Services. The Vice-Chairman is Herbert R. Temple, Jr., Director of the State Office of Emergency Services. Secretary was Wesley G. Bruer, State Geologist. The Council is guided by a nine-man Steering Committee consisting of the officers and one representative from each of the following categories: Federal agencies, State agencies, universities, local government, private organizations, and the public-at-large. Under the Steering Committee are the Preparedness and Response Committee and the Research and Investigations Committee, chaired by the Council Vice-Chairman and the Secretary, respectively. These last two committees are further divided into sub-committees. Many other individuals, in addition to formally appointed Council representatives and alternates, contribute their special expertise to the work of the sub-committees at the request of sub-committee chairmen.

The principal effort of the Council to date has been to review and evaluate the recommendations contained in several recent and comprehensive studies of earthquake hazards and to consider other feasible hazard-reduction measures. In addition to recommending that certain measures be taken, special attention will be given to means of implementing the recommendations. The great failing of most previous studies in earthquake-hazard reduction has not been in scope or content but in lack of follow-through; that is, no viable mechanism has been set in motion to carry out the recommendations effectively.

The primary thrust of Council recommendations is directed toward actions which may be taken administratively by all types of public and private entities, although not exclusively so. The primary thrust of recommendations developed by the Joint Committee on Seismic Safety has been toward legislation at the State level but again not to the exclusion of other kinds of recommendations.

The first report to the Governor by the Council was completed in November 1972 and was approved by Governor Ronald Reagan on December 12, 1972.

Other actions by the Council include the issuance of a statement on April 28 in support of Proposition 2 on the June 6 California primary election ballot to provide State financial assistance to school districts to bring schools up to earthquake-resistant standards as required by law by June 30, 1975. Proposition 2 was passed at the June 6 election. The Council also has prepared *Suggested interim guidelines for the seismic safety element in general plans* required by local governments. The *Guidelines* has now been distributed to city and county administrators under the letterhead of the California Council on Intergovernmental Relations which is represented on the Council.

CONCLUSION

The presentation of detailed recommendations for reducing future earthquake losses is beyond the scope of this paper. Indeed, it would be presumptuous to do so here in view of the massive efforts currently being made in this field by the Governor's Earthquake Council and the Legislature's Joint Committee on Seismic Safety, in which both authors of this paper are participating.

Recommendations are being made by these two organizations in dozens of categories, both legislative and administrative, including many dealing with: preparedness, response, and recovery; research in geology, seismology, and engineering; socio-economic, planning, and governmental response studies; construction of new facilities of all types; rehabilitation or abandonment of existing hazardous buildings, dams, bridges and other structures; insurance; information and education; and the creation of one or more successor coordinating bodies to carry on the work of implementing these recommendations.

Careful estimates of losses from future severe earthquakes, if experienced by urban areas in their present physical condition, anticipate fatalities in the thousands and damages in the billions of dollars. Most of these fatalities and some of the damages are preventable if the proper measures are taken before the disaster strikes. We strongly urge that the recommendations of the Joint Committee on Seismic Safety and of the Governor's Earthquake Council be given full consideration and support; most importantly, such of those recommendations as are approved by the Legislature and the Governor must be implemented quickly and thoroughly. The lives of thousands of Californians are in the balance.

One last word about the San Fernando earthquake: if the current efforts in earthquake-risk reduction—so greatly stimulated by that event—are successfully carried out, the San Fernando earthquake will indeed have achieved a significance far beyond that warranted by its Richter magnitude.

APPENDIX

Earthquake-Related Activities of California State Agencies [1]

OFFICE OF ARCHITECTURE AND CONSTRUCTION

The Office of Architecture and Construction has four specific functions: to enforce the Field Act, to do earthquake research and develop earthquake regulations and codes, to supervise design and construction of various state facilities assigned, and to report on repairs of disaster damage.

Since the Field Act was passed after the 1933 Long Beach earthquake, efforts have been directed toward minimizing the possibility of earthquake damage to school structures. The many investigations and reports (particularly, Meehan in this Bulletin) indicating low public school damage in the 1971 San Fernando earthquake attest to the success of this program.

Much information, gained from the review of the performance of school buildings exposed to earthquakes, has been used to develop new codes and enforcement procedures.

The design of State facilities to current lateral-force standards is a normal procedure in OAC's architectural and engineering development of projects. An example is the lateral-force resistance designed into the new Administration and Library Building at Hayward State University, where design criteria in excess of the minimum standards were incorporated in the structure because of the close proximity of the active Hayward fault. On-site construction supervision insures compliance with the requirements of the plans and specifications of the contract. Experiences with recently completed public buildings in the San Fernando area justify this approach.

OAC is involved in post-disaster investigation and reporting, whether the disaster is caused by an earthquake or by fire and floods. Acting as representatives of the Department of Finance and the State Office of Emergency Services, equitable costs are recommended for federal grants to local government to accomplish repair or replacement of damaged buildings, utilities, and other related projects. Investigation in the field actually commences on disaster day. The damage is assessed to assist the Governor in determining the magnitude of the disaster and to assist him in determination of the basis for requesting a Presidential declaration so that federal aid can be provided. Since the earthquake in 1971, OAC has investigated, inspected, and prepared reports on more than 2000 claims amounting to over $275 million. Much additional work remains to be done.

OFFICE OF EMERGENCY SERVICES

The Office of Emergency Services is authorized by the Emergency Services Act (Chapter 7 of Division 1 of Title 2 of the Government Code), which places it within the Governor's Office.

The Act designates the Director as the State Director of Civil Defense and State Emergency Planning and further

[1] Adapted from statements prepared by agencies of the State and presented to the Governor's Earthquake Council by Robert B. Jansen on February 28, 1972.

states, "During a state-of-war emergency, a state of emergency, or a local emergency, the Director shall coordinate the emergency activities of all state agencies in connection with such emergency." The act also charges the Office to develop and maintain the State Emergency Plan, which is the basis for state agency and local government emergency plans.

The Office maintains a communications center, through which the Governor's Office receives a flow of information from every geographic and organizational area of the state. A State agency or a local government official may notify the Office that a disaster exists or is imminent. Immediate notification may make it possible to anticipate an emergency and blunt its effects by accelerated preparations or even to prevent an emergency from enlarging to disaster proportions.

The Office administers and coordinates federal disaster relief activities and federal financial support in recovery efforts after a major disaster has been declared under the authority of Public Law 91-606.

The Office is responsible for coordinating State agencies in developing postdisaster damage assessment, including input from local governments and the private sector.

The responsibilities of OES are not limited to earthquakes, nor are they significantly different for other major emergencies.

DIVISION OF HIGHWAYS

The responsibility for the operation of the state highway system, which forms the framework upon which the major portion of the state's vehicles travel, imposes a heavy obligation to maintain communications, even in times of disaster.

The objective of the Division of Highways, which is in the Department of Public Works, is to prevent any traffic disruption and, in the event of such catastrophes as earthquakes and floods, to restore traffic facilities, at least temporarily, as soon as possible.

It is impossible to design structures so as to prevent all damage; the forces involved are too overpowering to be fully resisted. It is to be expected that highway structures caught in the focal area of destruction, as some were in San Fernando, will be considerably damaged. On the other hand, the Division of Highways feels a great responsibility to prevent any loss of life and is dedicated to a program of designing highway structures that will not collapse.

The valuable lessons learned from the San Fernando earthquake were immediately incorporated into all the designs then in preparation and into all the bridges then under construction. A program has been instituted to go back into existing bridges which contain demonstrated weaknesses and strengthen them.

A number of design refinements are being made to correct demonstrated weaknesses. In addition, there are several research programs underway seeking to develop dynamic designs for earthquake resistance. These recognize that the violent motion to which the structures may be subjected can, in some cases, because of the additive nature of the wave motions build up forces considerably higher than derived from the application of static forces. These studies should enable more realistic determination of forces and movements and lead to more adequate designs. The design philosophy is that, while it is to be expected that some damage will result from a severe earthquake, every effort must be made to prevent total collapse.

Contracts are being let in a continuing program to review existing structures to improve earthquake resistability.

DEPARTMENT OF HOUSING AND COMMUNITY DEVELOPMENT

The enabling authority for the Department of Housing and Community Development may be found in the California Health and Safety Code and the Labor Code.

In the area of earthquake-related responsibilities and activities, the Department has responsibility for development, interpretation, and enforcement of statewide building and housing standards.

The Department also works closely with other concerned State agencies in the development of building standards applicable to all building occupancies.

DEPARTMENT OF INSURANCE

This Department regulates insurance companies transacting business in California under authority granted in the Insurance Code. The regulatory objectives of the Department relate to assuring the solvency of the companies providing coverage to California policyholders and to the practices of those companies as they affect public interest. Specifically, companies providing earthquake coverage do so under a competitive system wherein the rates which apply to the coverage afforded must be adequate to insure solvency, not unreasonably high for the insurance afforded, and not unfairly discriminatory.

Because of the importance of insurance as a potential factor in long-term rehabilitation of property damage caused by earthquakes, the Department of Insurance has taken an active interest in the availability of earthquake insurance and the problems inherent in underwriting this type of coverage. As a member of the National Association of Insurance Commissioners subcommittee on the availability of essential insurance, the Department has participated in development of a program being presented to the private insurance industry that could lead to universal earthquake coverage on homes and small businesses while, at the same time, assuring that the effects of a catastrophe would not render insurance companies insolvent.

COUNCIL ON INTERGOVERNMENTAL RELATIONS

The Council on Intergovernmental Relations is most directly involved in earthquake-related activities through the recently adopted amendment to the State Planning Law, which requires all cities and counties to adopt seismic safety elements as part of their general plans. CIR provides both technical and financial assistance to local government in the preparation of their general plans.

CIR distributed "Suggested Interim Guidelines For The Seismic Safety Element," as prepared by the Governor's Earthquake Council, to all local governments in July 1972.

In order to provide more advanced guidelines for the preparation and content of seismic safety elements, CIR has developed a demonstration seismic safety element project. A $66,000 grant has been earmarked for a three-city seismic safety program to be conducted in 1972–73 in San Pablo, El Cerrito, and Richmond in western Contra Costa County. The California Division of Mines and Geology is preparing the geologic studies under contract with these local governments.

CIR staff is also currently reviewing and preparing recommendations for revising the State Planning and Zoning Law. The seismic safety element requirement of the State Planning Law will also be considered in relation to other planning considerations.

DIVISION OF MINES AND GEOLOGY

The responsibilities of the California Division of Mines and Geology in the Department of Conservation are as follows: (a) to represent the State's interest in information pertaining to earthquake and other geologic hazards; (b) to conduct, with city and county governments or federal and other state agencies, large-scale geological investigations to identify and provide timely delineation of geological hazards in and adjacent to metropolitan areas; (c) to organize and monitor a strong-motion instrumentation program in the state of California; and (d) to identify quickly potential post-earthquake geologic hazards, particularly weakened slopes, that could be activated by aftershocks.

The Division's authority is provided in the Public Resources Code. Its objectives are to reduce losses of life and property caused by earthquakes by timely identification and delineation of earthquake hazards and by providing ground-motion response data useful in designing and building structures to resist earthquake damage. A significant addition to the Division's earthquake responsibilities came in March 1973 when SB 520 requiring the State Geologist to designate hazardous fault zones became law.

The earthquake-related activities include: (a) Geodimeter surveys along the San Andreas fault system to measure changes in the accumulation of crustal strain; (b) tiltmeter monitoring of the San Andreas fault system for differential vertical changes; (c) installation of strong-motion instruments on carefully selected soil and rock sites and structures throughout the state; (d) mapping surface breaks and earthquake-triggered landslides in the vicinity of such recent earthquakes as the 1971 San Fernando earthquake; (e) publication of information on earthquakes as a means of public education; (f) preparation of a geologic map of California showing faults, classified as to their recency of movement; (g) cooperating with various counties and cities in preparing seismic hazard analyses and providing information necessary for the preparation of seismic safety elements of general plans; (h) mapping critical segments of active faults; (i) providing data on seismic risk to California Power Plant Siting Committee; (j) performing required staff work for the Governor's Earthquake Council; (k) as a part of the HUD-Urban Geology Master Plan project, preparation of maps of California showing tsunami vulnerability, historic earthquake recurrence, expectable earthquake intensity, and historic earthquake epicenters; and (*l*) serving as a clearinghouse for crustal-strain monitoring activities and programs and instrumentation in California by publication of a newsletter.

MINING AND GEOLOGY BOARD

The functions of the Mining and Geology Board are set forth in the Public Resources Code, Section 667, as follows:

> "The board shall represent the State's interest in the development, utilization and conservation of the mineral resources of the state, and in the development, collection, collation and dissemination of geologic information necessary to the understanding and utilization of the state's terrain *and in information pertaining to earthquake and other geologic hazards*. It may establish policies conforming to the provisions of State statutes to govern the administration of the Division of Mines and Geology"

The Board advises the California Division of Mines and Geology and the Department of Conservation on policies and recommendations for programs in the field of earthquakes and other geologic hazards. The Geologic Hazards Committee of the Board consists of a geologist member, a seismologist member, and a structural engineer member. Members of this committee are active in a wide range of groups involved in earthquake studies of various kinds; they bring a broad overview of activities conducted in this field to the Board, the Division, and the Department and, conversely, disseminate information to other groups about the earthquake-related activities of the California Division of Mines and Geology.

OFFICE OF PLANNING AND RESEARCH

The Office of Planning and Research in the Governor's Office is in the process of preparing a statewide plan and implementation program for protecting land and water resources which are of statewide significance in terms of California's natural resource base and the preservation and enhancement of environmental quality as required by Government Code Section 65049. An example of the areas to be covered includes "areas which require special development regulation because of hazardous or special conditions such as earthquake fault zones, unstable slide areas, flood plains and watersheds."

Another area of responsibility for OPR is the evaluation of environmental impact statements. Although the evaluation is specifically from the standpoint of land use and population, these two areas are related to any potential adverse effect they may have on the environment, as well as any potential adverse effect the environment (earthquakes, etc.) may have on them.

In addition, OPR is coordinating the development and operation of a statewide environmental-monitoring system to assess the implications of present growth and development trends on the environment and to identify, at an early time, potential threats to public health, natural resources, and environmental quality. This bears an obvious relationship to earthquake-hazard prevention and related early warning systems.

DEPARTMENT OF REAL ESTATE

One of the functions of the Department of Real Estate is to administer the Subdivided Lands Act. This Act provides, in part, that a subdivider is required to give a copy of the subdivision public report prepared by the Department of Real Estate to each prospective purchaser of a lot or parcel in a subdivision. The Department, in this public report, discloses whether geological conditions are such as to constitute a hazard to the tract or structures thereon.

The Department's responsibility regarding earthquake-related conditions is one of full disclosure to the first purchaser or prospective purchaser of lots or parcels in a subdivision.

DEPARTMENT OF WATER RESOURCES

The Department of Water Resources is responsible for construction and operation of the State Water Project and for the safety of dams in California, other than those federally owned. Authority for conducting earthquake-related investigations derives from this responsibility. The objective of these programs is to develop the data and technology required to construct and maintain safe, economical, and reliable water-supplies and facilities and to assure the safety of dams.

In 1958, a Consulting Board for Earthquake Analysis was created which has continued to provide guidance in formulating and implementing a comprehensive program of seismological and earthquake engineering investigations. This Board consists of five authorities representing seismology, geology, structural engineering, soil mechanics, and construction practices.

The Department's seismic investigations fall into three categories:

1. Identification and evaluation of earthquake-related hazards at sites for dams and water-supply facilities.
2. The study of seismic-related ground motions and deformations and the response of superimposed structures.
3. The design of dams and water-project facilities to withstand earthquake effects.

The DWR Sacramento headquarters serves as a focal point for a cooperative, statewide network of stations selected from six separate networks of seismographs operated by the California Institute of Technology, University of Nevada, National Oceanic and Atmospheric Administration, University of California, U.S. Geological Survey, and California Department of Water Resources. Seismic disturbances detected by these instruments are telemetered to Sacramento where they are displayed by lights on maps. The Control Center, which is manned continuously, is thus alerted to the location of any significant earthquakes with respect to dams and elements of the State Water Project. This cooperative seismograph network is the only one in California which approaches statewide coverage.

The Department also sponsors a strong-motion seismograph program, comprised of 91 seismoscopes and 51 accelerometers. These instruments are located near facilities of the State Water Project and on structures of the State Water Project. This program has evolved to meet requirements for analysis procedures and design which are an outgrowth of new knowledge of earthquakes and of the dynamic properties of materials. The systems are triggered during a seismic event to record accelerations, stresses, and hydraulic pressures of a dynamic and transient nature.

Output from the instrumentation program is evaluated, following all significant seismic disturbances, in a continuing endeavor to improve earthquake-design criteria. Valuable information was obtained from DWR-NOAA instruments during the Parkfield earthquakes of June 27, 1966, and the San Fernando earthquakes of February 9, 1971.

Due to the unparalleled events accompanying the San Fernando earthquake of February 9, 1971, DWR's Division of Safety of Dams has increased its earthquake-engineering program substantially. An engineering investigation of the effects on Van Norman Reservoir Complex was initiated to determine the mechanism of the slides in the two hydraulic-fill dams. The Division has required owners of other hydraulic-fill dams to conduct earthquake-engineering investigations and will require strengthening of any dam not found earthquake resistant. The Division is also helping a county-organized task force to prepare a report advising the Los Angeles County Board of Supervisors on those recommendations of the Los Angeles County Earthquake Commission which relate to dams.

Section 6

Consolidated References

CONSOLIDATED REFERENCES

Aboudi, J., 1971. The motion excited by an impulsive source in an elastic half-space with a surface obstacle: Bull. of the Seismological Society of America, v. 61, no. 3, p. 747–763.

Adair, John D., and Iungerich, Russell, 1972. Insuring the earthquake hazard: Los Angeles Bar Bull., Feb., p. 155–163.

Albritton, C. C., Jr., and Smith, J. F., 1957. The Texas lineament: International Geological Congress, 20th, Mexico, D.F., 1956, v. 2, sec. 5, p. 501–518.

Alf, R. M., 1948. A mylonite belt in the southeastern San Gabriel Mountains, California: Geological Society of America Bull., v. 59, p. 1101–1119.

Algermissen, S. T., 1969. Seismic risk studies in the United States: Proceedings Fourth World Conference on Earthquake Engineering, 9 p. plus maps and tables.

Allen, C. R., 1957. San Andreas fault zone in San Gorgonio Pass, southern California: Geological Society of America Bull., v. 68, p. 315–350.

Allen, C. R., 1968. The tectonic environments of seismically active and inactive faults along the San Andreas fault system *in* Proceedings of Conference on Geologic Problems of the San Andreas Fault System: Stanford University Publications Geological Sciences, v. XI, p. 70–82.

Allen, C. R., Engen, G. R., Hanks, T. C., Nordquist, J. M., and Thatcher, W. R., 1971. Main shock and larger aftershocks of the San Fernando earthquake, February 9 through March 1, 1971 *in* U.S. Geological Survey Professional Paper 733, p. 17–20.

Allen, C. R., and Housner, G. W., 1967. See *Resources Agency*.

Allen, C. R., St.-Amand, P., Richter, C. F., and Nordquist, J. M., 1965. Relationship between seismicity and geologic structures in the southern California region: Bull. of the Seismological Society of America, v. 55, no. 4, p. 753–797.

Anderson, Don L., 1971. The San Andreas fault: Scientific American, Nov., p. 53–68.

Bailey, T. L., 1954. Geology of the western Ventura Basin, Santa Barbara, Ventura, and Los Angeles Counties, *in* Jahns, R. H., *ed.*, Geology of southern California: California Division of Mines Bull. 170, map sheet 4.

Bailey, T. L., and Jahns, R. H., 1954. Geology of the Transverse Range province, southern California, *in* Jahns, R. H., *ed.*, Geology of southern California: California Division of Mines Bull. 170, chapter 2, contribution 3, p. 83–106.

Baird, A. K., Welday, E. E., and Baird, K. W., 1970. Chemical variations in batholithic rocks of southern California (abstract): Geological Society of America, 66th Annual Cordilleran Section meeting, Hayward, California, p. 69.

Baird, A. K., Baird, K. W., Woodford, A. O., and Morton, D. M., 1971. The Transverse Ranges: a unique structural-petrochemical belt across the San Andreas fault system (abstract): Geological Society of America, 67th Annual Cordilleran Section meeting, Riverside, California, p. 77–78.

Baker, C. L., 1933. Rotational stress as possible cause of fundamental crustal deformation: Pan-American Geologist, v. 59, p. 19–32.

Baker, C. L., 1934. Major structural features of Trans-Pecos Texas, *in* E. H. Sellards et al., The geology of Texas, v. 2, Structural and economic geology: Texas University Bull. 3401, p. 137–214.

Barbat, W. F., 1958. Los Angeles Basin area, California, *in* Higgins, J. W. (ed.), A guide to the geology and oil fields of the Los Angeles and Ventura regions: Pacific Section American Association of Petroleum Geologists, p. 37–49.

Barnes, D. F., 1966. Gravity changes during the Alaska earthquake: Journal Geophysical Research, v. 71, no. 2, p. 451–456.

Barnes, D. F., 1969. Effects of geologic processes on the gravity anomolies at the southern Alaska continental margin (abstract): EOS, v. 50, no. 11, p. 604.

Barnes, D. F., Oliver, H. W., and Robbins, S. L., 1969. Standardization of gravimeter calibrations in the Geological Survey: EOS, v. 50, no. 10, p. 526–527.

Barnhart, J. T., Esmilla, A. B., Larsen, G. R., Murphy, R. D., and Slosson, J. E., 1966. Santa Susana Mountains: American Association of Petroleum Geologists, Pacific Section, Spring Field Trip Guidebook, 9 p.

Barrows, A. G., Kahle, J. E., Weber, F. H., Jr., and Saul, R. B., 1971. Map of surface breaks resulting from the San Fernando, California, earthquake of February 9, 1971: California Division of Mines and Geology Preliminary Report 11.

Beatie, R. L., 1958. The geology of the Sunland-Tujunga area, Los Angeles County, California: University of California, Los Angeles, unpublished M.A. thesis, 102 p.

Benioff, H., 1955. Mechanism and strain characteristics of the White Wolf fault as indicated by the aftershock sequence in Earthquakes in Kern County, California, during 1952: California Division of Mines Bull. 171, p. 199–202.

Benioff, H., 1959. Fused-quartz extensometer for secular, tidal, and seismic strains: Geological Society of America Bull., v. 70, p. 1019–1032.

Bishop, R. J., 1950. Geology of the southern flank of the Santa Susana Mountains: University of California, Los Angeles, unpublished M.A. thesis, 115 p.

Bolt, B. A., 1970. Elastic waves in the vicinity of the earthquake source *in* Earthquake Engineering, R. Wiegel, *Ed.*: Prentice Hall.

Bolt, B. A., 1971a. The San Fernando Valley, California, Earthquake of February 9, 1971, Data on seismic hazards: Bull. Seismological Society of America, v. 61, p. 501–510.

Bolt, B. A., 1971b. Recommendation on seismic risk to the Veterans' Administration, Hearings before a special subcommittee of the Committee on Veterans' Affairs: House of Representatives, U.S. Government Printing Office.

Bonilla, M. G., 1967. Historic surface faulting in continental United States and adjacent parts of Mexico: U.S. Geological Survey Interagency Report Reactor siting research (open file).

Bonilla, M. G., 1959. Geologic observations in the epicentral area of the San Francisco earthquake of March 1957: California Division of Mines Special Report 57, p. 25–37.

Bonilla, M. G., et al., 1971. Surface faulting *in* Preliminary report on the San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733.

Bonilla, M. G., 1972. Detailed study of parts of the 1971 surface faulting in the San Fernando fault zone (abstract): Investigations of the San Fernando earthquake, National Conference on Earthquake Engineering, Los Angeles, California, February 7–9, 1972, Program p. 5.

Bonilla, M. G. (in press). Trench exposures of parts of the February 9, 1971 surface faults in the San Fernando fault zone, *in* (report on the San Fernando earthquake): Earthquake Engineering Research Institute/National Oceanic and Atmospheric Administration.

Boore, D. M., 1972. A note on the effect of simple topography on seismic SH waves: Bull. of the Seismological Society of America, v. 62, no. 1, p. 275–284.

Bostron, R. C., and Couch, R. W., 1968. An observation program on level changes and the incidence of seismicity in the Puget Sound area: Trend in Engineering at the University of Washington, v. 20, no. 2, p. 18–20.

Brady, A. G., and Hudson, D. E., 1970. Strong-motion earthquake accelerograms—Digitized and plotted data: Earthquake Engineerinig Research Laboratory, California Institute of Technology, Pasadena, v. I, Part B, Rpt. No. EERL 70-21.

Brady, A. G., Hudson, D. E., and Trifunac, M. D., 1971. Strong-motion earthquake accelerograms—Digitized and plotted data: Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, Report No. EERL 71-20, v. I, Part C.

Brandow and Johnson, Associates, 1971. Report on investigation of damage to structures at the Veterans Administration Hospital, 13000 Sayre Street, San Fernando, California: Unpublished.

Brown, R. D., Jr., and Wallace, R. E., 1968. Current and historic fault movement along the San Andreas fault between Paicines and Camp Dix, California: Proceedings of Conference on Geologic Problems of San Andreas Fault System, Stanford University Publications in Geological Sciences, v. XI, p. 22–41.

Burchfiel, B. C., and Davis, G. A., 1970. A zwischenberge in the Cordilleran orogen and its tectonic significance: Geological Society of America, South-Central Section meeting, College Station, Texas.

Burford, Robert O., 1967. Recent strain changes across the San Andreas fault and Coast Ranges at Hollister and Cholame, California: Unpublished Ph.D. thesis, Stanford University Department of Geological Sciences.

Burford, R. O., *in press* 1972. Creep on the Coyote Creek fault following the Borrego Mountain earthquake of 9 April 1968.

Burford, R. O., Castle, R. O., Church, J. P., Kinoshita, W. T., Kirby, S. H., Ruthven, R. T., and Savage, J. C., 1971. Preliminary measurements of tectonic movement *in* The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 80–85.

Buwalda, J. P., 1940, Geology of the Raymond basin: Private report prepared for City of Pasadena.

Byerlee, J. D., and Brace, W. F., 1968. Stick-slip, stable sliding, and earthquakes—effect of rock type, pressure, strain rate, and stiffness: Journal of Geophysical Research, v. 73, no. 18, p. 6031–6037.

California Department of Public Works, Division of Water Resources, 1934. South coastal basin investigation, geology and ground water storage capacity of valley fill: Bull. 45.

California Department of Public Works, Division of Water Resources, 1943. Report of Referee in the Superior Court of the State of California in and for the County of Los Angeles, City of Pasadena v. City of Alhambra et al.: No. Pasadena C1323 (Raymond Basin).

California Division of Mines and Geology, Active faults of California: Mineral Information Service, v. 22, no. 5, May 1969, p. 80–81.

California Division of Mines and Geology, California Geology, April–May 1971, San Fernando earthquake edition.

California Division of Oil and Gas, 1962. Summary of operations of California oil fields, 256 p.

California Division of Oil and Gas, 1964. Exploratory wells drilled outside of oil and gas fields in California to December 31, 1963: 319 p.

California Division of Oil and Gas, 1969. Summary of operations of California oil fields, 132 p.

California Institute of Technology, 1971. The San Fernando earthquake, *in* CIT Engineering and Science, March, p. 4–15.

California State Water Rights Board, 1962. Report of Referee, City of San Fernando, California Superior Court, County of Los Angeles, no. 650079: California State Water Rights Board, v. 1, 258 p.

Campbell, R. H., Yerkes, R. F., and Wentworth, C. M., 1966. Detachment faults in the central Santa Monica Mountains, California: U.S. Geological Survey Professional Paper 550-C, p. 1–11.

Campbell, R. H., and Yerkes, R. F., 1971. Cenozoic evolution of the Santa Monica Mountains—Los Angeles basin area: II. Relations to plate tectonics of the northeast Pacific Ocean: Geological Society of America Cordilleran Section meeting, Riverside, California, p. 92.

Canitez, N., and Toksoz, M. N. (in press) 1972. Static and dynamic study of earthquake source mechanisms—San Fernando earthquake: Journal of Geophysical Research, v. 77, no. 14, p. 2583–2594.

Carter, Bruce, and Silver, Leon T., 1971. Post-emplacement structural history of the San Gabriel anorthosite complex: Geological Society of America, Abstracts of Cordilleran Section, p. 92–93.

Cassell, J. K., and Sanem, R. E., 1962. The Mission oil field: American Association of Petroleum Geologists, Pacific Section, Spring Field Trip Guidebook, p. 12.

Chapman, R. H., 1966. Gravity base station network: California Division of Mines and Geology Special Report 90, 49 p.

Chapman, R. H., 1969. Gravity surveys in California—recent progress by the California Division of Mines and Geology: EOS, v. 50, no. 10, p. 542–543.

Cloud, W. K., 1964. The cooperative program of earthquake investigation *in* Earthquake investigations in the western United States, 1931–1964 (D. S. Carder, ed.): Publication 41-2, Coast and Geodetic Survey, U.S. Department of Commerce.

Cloud, W. K., and Maley, R. P., 1970. Building-period measurements during an earthquake with comments on instruments: Proceedings of Conference on Earthquake Analysis of Structures, Isai, Romania.

Cloud, W. K., and Perez, V., 1970. Strong motion—Records and acceleration: Proceedings of Fourth World Conference on Earthquake Engineering, Santiago, Chile.

Corbató, C. E., 1960. Gravity investigation of San Fernando Valley, California: University of Cailfornia at Los Angeles unpublished Ph.D. thesis.

Corbató, C. E., 1963. Bouguer gravity anomalies of the San Fernando Valley, California: California University Publications in Geological Sciences, v. 46, no. 1, p. 1–32.

Cordova, Simon, 1965. Horse Meadows oil field: California Division of Oil and Gas Summary of Operations, v. 51, no. 2, p. 61–65, pls. II, III, and IV.

Crandall, LeRoy, 1971. Opinions on soil and foundation behavior during San Fernando earthquake, Olive View Hospital and Juvenile Facility, SEAOSC AD HOC COMMITTEE *in* Report on Olive View Hospital: Structural Engineers Association of Southern California, Exhibit C.

Crowell, J. C., 1952. Probable large lateral displacement on San Gabriel fault, southern California: American Association of Petroleum Geologists Bull., v. 36, p. 2026–2035.

Crowell, J. C., 1954. Strike-slip displacement of the San Gabriel fault, southern California, *in* Johns, R. H., *Ed.*, Geology of southern California: California Division of Mines Bull. 170, Ch. 4, Contribution 6, p. 49–52.

Crowell, J. C., 1962. Displacement along the San Andreas fault, California: Geological Society of America Special Paper 71, 61 p.

Crowell, J. C., 1968. Movement histories of faults in the Transverse Ranges and speculations on the tectonic history of California: Proceedings of Conference on Geologic Problems of San Andreas Fault System; Stanford University, p. 323–341.

Crowell, J. C., 1971. Tectonic problems of the Transverse Ranges, California: Geological Society of America, Abstract, Cordilleran Section meeting, Riverside, California, p. 106.

Crowell, J. C., and Walker, J. W. R., 1962. Anorthosite and related rocks along the San Andreas fault, southern California: California University Publications in Geological Sciences, v. 40, no. 4, p. 219–288.

Daviess, S. N., and Woodford, A. O., 1949. Geology of the northwestern Puente Hills, Los Angeles County, California: U.S. Geological Survey Oil and Gas Inventory Preliminary Map 83.

Dibblee, T. W., Jr., 1967. Areal geology of the western Mojave Desert, California: U.S. Geological Survey Professional Paper 522, 153 p.

Dibblee, T. W., Jr., 1968. Displacements on the San Andreas fault system in the San Gabriel, San Bernardino, and San Jacinto Mountains, southern California, *in* Dickinson, W. R., and Grantz, Arthur, *Eds.*, Proceedings of Conference on Geologic Problems of San Andreas Fault System: Stanford University Publications in Geological Sciences, v. XI, p. 260–276.

Dillinger, W., and Espinosa, A. F., 1971. Preliminary fault-plane solution for the San Fernando earthquake, *in* The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 142–152.

Division of Geological and Planetary Sciences, California Institute of Technoolgy, 1971. Preliminary seismological and geological studies of the San Fernando, California, earthquake of February 9, 1971: Bull. Seismological Society of America, v. 61, p. 491–495.

Donnan, W. W., Litz, G. M., and Aronovici, V. S., 1950. Ground water and drainage investigations in San Fernando Valley, Los Angeles County, California: U.S. Department of Agriculture, Soil Conservation Service, Research.

Dudley, Paul, Jr., 1954. Geology of the area adjacent to the Arroyo Seco Parkway, Los Angeles County, California: University of California at Los Angeles, unpublished master's thesis.

Duerksen, J. A., 1949. Pendulum gravity data in the United States: U.S. Coast and Geodetic Survey Special Publication no. 244, 218 p.

Duke, C. Martin, 1971. Damage to water supply systems, *in* The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 225–240.

Earthquake Engineering Research Institute—National Oceanic and Atmospheric Administration special volume on the San Fernando earthquake, in press 1973.

Eckis, Rollin, 1928. Alluvial fans in the Cucamonga district, southern California: Journal of Geology, v. 36, p. 224–247.

Eckis, Rollin, 1934, South coast basin investigation: California Division Water Resources Bull. 45, 279 p.

Edwards, L. N., 1971. Paleogeographical interpretation of the Vaqueros and Rincon Formations, Ventura basin, California: Geological Society of America Abstract for Cordilleran Section meeting, Riverside, California, p. 115.

Ehlig, P. L., 1958. Geology of the Mount Baldy region of the San Gabriel Mountains, California: California University, Los Angeles, unpublished Ph.D. thesis, 153 p.

Ehlig, P. L., 1959. Relationship of the Pelona Schist and Vincent thrust in the San Gabriel Mountains, California, abstract, Geological Society of America, Bull. v. 70, p. 1717.

Ehlig, P. L., 1966. Displacements along the San Gabriel fault, San Gabriel Mountains, southern California: Geological Society of America, Abstract for national meeting, San Francisco, California, p. 60.

Ehlig, P. L., 1968. Causes of distribution of Pelona, Rand, and Orocopia Schist along the San Andreas and Garlock faults, in Dickinson, W. R., and Grantz, Arthur, *Eds.*, Proceedings of Conference on Geologic Problems of San Andreas Fault System: Stanford University Publications in Geological Sciences, v. XI, p. 294–305.

Eldridge, G. H., and Arnold, Ralph, 1907. The Santa Clara Valley, Puente Hills, and the Los Angeles oil districts: U.S. Geological Survey Bull. 309, 266 p.

Ellingwood, C. F., and Williamson, R. O., 1971. Control resurveys and the San Fernando earthquake (a preliminary analysis) in Papers from the 1971 ASP-ACSM Fall Convention, American Congress on

Surveying and Mapping, September 7–11, 1971, San Francisco, California: paper 71-391, p. 148–178.
English, W. A., 1914. The Fernando Group near Newhall, California: University of California Publications Bull. Department of Geology, v. 8, no. 8, p. 203–218.
Espinosa, A. F., Engdahl, E. R., Tarr, A. C., and Brockman, S., 1971. A preliminary report of near-field seismic monitoring of the San Fernando aftershock series, p. 135–141, *in* The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733.
Esteva, L., and Nieto, J. A., 1967. El temblor in Lima, Peru, Octobre 17, 1966: Revista Ingenieria, Mexico, v. XXXVII.
Evernden, J. F., and Kistler, R. W., 1970. Chronology of emplacement of Mesozoic batholithic complexes in California and western Nevada: U.S. Geological Survey Professional Paper 623, 42 p.
Fallgren, R. B., and Smith, J. L., 1971a. Geologic and soil investigation, San Fernando Valley Juvenile Hall, Sylmar, California, conducted for County Engineer, County of Los Angeles, by Fugro Inc., Sept. 20, 1971: Unpublished, 45 p.
Fallgren, R. B., and Smith, J. L., 1971b. Geologic and soil investigation, Sylmar Converter Station, Sylmar, California: Unpublished report prepared for the Department of Water and Power, City of Los Angeles, October 5, 1971.
Fischer, J. A., and Murphy, W. J., 1970. Design criteria for nuclear power plants.
Frazier, G. A., Wood, J. H., and Housner, G. W., 1971. Earthquake damage to buildings, *in* Jennings, P. C., ed., Engineering features of the San Fernando earthquake of February 9, 1971: Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, EERL Rept. 71-02, p. 140–298.
Fugro, Inc., 1971. Geologic and soil investigation, San Fernando Juvenile Hall, Sylmar, California: Unpublished report prepared for County of Los Angeles, Sept. 20, 1971.
Geodetic Section—Survey Division, Department of County Engineer, County of Los Angeles, 1971. Land movement studies relating to the San Fernando earthquake of February 9, 1971: Los Angeles County Engineer, unpublished report.
George, J. W., 1937. Geologic report on a portion of the Little Tujunga quadrangle and a portion of the Sunland quadrangle: California Institute of Technology, Pasadena, unpublished B.S. thesis, 19 p.
Gibbs, H. J., and Holtz, W. G., 1957. Research on determining the density of sand by spoon penetration test: Proceedings of Fourth International Conference on Soil Mechanics and Foundation Engineering, v. 1, p. 35–39.
Gilluly, James, 1970. Crustal deformation in the western United States, *in* Johnson, Helgi, and Smith, B. L., *Ed.*, The megatectonics of continents and oceans: Rutgers University Press, New Jersey, p. 47–112.
Gilluly, James, Waters, A. C., and Woodford, A. O., 1968. Principles of geology: W. H. Freeman and Co., San Francisco, 687 p.
Governor's Earthquake Council, 1972. Suggested interim guidelines for the seismic safety element in general plans: Unpublished report, available from California Division of Mines and Geology.
Governor's Earthquake Council, 1972. Minutes of the meeting of February 28, 1972: Jansen, Robert B., Abstract of earthquake-related activities of California State agencies. Unpublished report, available from California Division of Mines and Geology.
Grannell, R. B., and Biehler, Shawn, 1971. A regional gravity survey of the San Gabriel Mountains, California (abstract): Geological Society of America, Cordilleran Section, 67th Annual Meeting, Abstracts with programs, v. 3, no. 2, p. 127.
Greensfelder, Roger, 1971. Seismologic and crustal movements investigations of the San Fernando earthquake: California Division of Mines and Geology, California Geology, v. 24, no. 4-5, p. 62–68.
Greensfelder, Roger W., and Crice, Douglas, 1971. Geodimeter fault movement investigations in California: California Division of Mines and Geology, California Geology, v. 24, no. 6, p. 105–109.
Gutenberg, B., 1957. Effects of ground on earthquake motion: Bull. Seismological Society of America, v. 47, no. 3, July, p. 221–252.
Hagiwara, T., and Rikitake, T., 1967. Japanese program on earthquake prediction: Science, v. 157, p. 761–768.
Hanks, T. C., Jordan, T. H., and Minster, J. B., 1971. Precise locations of aftershocks of the San Fernando earthquake 2300 (GMT) February 10–1700 February 11, 1971, *in* The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 21–23.
Hanson, A. C., and Saunders, J. M., 1962. Aliso Canyon oil field: American Association of Petroleum Geologists, Pacific Section, Spring Field Trip Guidebook, p. 4–5.
Harrison, J. C., and Corbató, C. E., 1965. The Mount Wilson calibration range—new geodetic measurements in the western United States and some submarine gravity measurements in the northeastern Pacific Ocean: American Geophysical Union Transactions, v. 46, no. 1, p. 212–214.
Hazzard, J. C., 1944. Some features of Santa Susana thrust, vicinity of Aliso Canyon field, Los Angeles County, California (abstract): American Association of Petroleum Geologists Bull. v. 28, p. 1780–1781.
Heiland, C. A., 1946. Geophysical exploration: Prentice-Hall, Inc., New York, 1013 p.
Hershey, O. H., 1902. Some Tertiary formations of southern California: The American Geologist, v. 29, p. 350–357.
Higgs, D. V., 1954. Anorthosite and related rocks of the western San Gabriel Mountains, southern California: California University Geological Sciences Publications, v. 30, p. 171–222.
Hileman, James A., Allen, C. R., Brune, J. N., and Wyss, Max, 1971. Measurement of active slip on faults in the Imperial Valley region, California: Abstract *in* Program of the Cordilleran Section, Geological Society of America, 67th annual meeting, Riverside, California, p. 136.
Hill, M. L., 1930. Structure of the San Gabriel Mountains, north of Los Angeles, California: University California Publications Geological Sciences, v. 19, no. 6, p. 137–170.
Hill, M. L., 1954. Tectonics of faulting in southern California, p. 5–14 *in* Jahns, R. H. (Ed.), Geology of southern California, Chap. 4—structural features: California Division of Mines Bull. 170, 59 p.
Hill, Mary R., 1972. A centennial—the great Owens Valley earthquake of 1872: California Division of Mines and Geology, California Geology, March 1972, p. 51–54.
Hill, R. T., 1902. The geographic and geologic features and their relationship to the mineral products of Mexico: Transactions American Institute of Mining Engineers, v. 32, p. 163–178.
Hill, R. T., 1928. Transcontinental structural digression: Geological Society of America, v. 39, p. 265.
Hills, E. S., 1963. Elements of structural geology: John Wiley and Sons, New York, 483 p.
Hoffman, Renner B., et al., 1968. Geodimeter fault-movement investigations in California: California Department of Water Resources, Bull. 116-6.
Holloway, J. M., 1940. Areal geology and contact relations of the basement complex and later sediments, west end of the San Gabriel Mountains, California: California Institute of Technology, Pasadena, unpublished M.S. thesis, 25 p.
Holmes, L. C., Eckmann, E. C., Harrington, G. L., Guernsey, J. E., and Zinn, C. J., 1917. Soil survey of the San Fernando Valley area, California: U.S. Department of Agriculture, Washington, D.C., in cooperation with the University of California Agricultural Experiment Station, 61 p.
Holston, A. S., 1952. Aliso Canyon Oil Field *in* Cenozoic correlation section across eastern Ventura Basin from basement north of Oak Canyon oil field to Aliso Canyon oil field: American Association of Petroleum Geologists, 1952.
Hoots, H. W., 1930. Geology of the eastern part of the Santa Monica Mountains, Los Angeles County, California: U.S. Geological Survey Professional Paper 165, p. 83–134.
Housner, G. W., 1962. The significance of the natural periods of vibration of structures: Primeras Jornadas Argentinas de Ingenieria Antisismica, San Juan-Mendoza, Argentina.
Housner, G. W., 1970. Strong ground motion *in* Earthquake Engineering (R. W. Wiegel, ed.): Prentice-Hall Inc., Englewood Cliffs, N. J., p. 75–91.
Howell, B. F., Jr., 1949. Structural geology of the region between Pacoima and Little Tujunga Canyons, San Gabriel Mountains, California: California Institute of Technology, Pasadena, unpublished Ph.D. thesis, 110 p.
Howell, B. F., Jr., 1954. Geology of the Little Tujunga area, Los Angeles County, *in* Johns, R. H., Ed., Geology of southern California: California Division of Mines Bull. 170, map sheet 10.
Hsu, K. J., 1955. Granulites and mylonites of the region about Cucamonga and San Antonio Canyons, San Gabriel Mountains, California: University of California Publications in Geological Sciences, v. 30, p. 223–324.
Hsu, K. J., Edwards, George, and McLoughlin, W. A., 1963. Age of the intrusive rocks of the southeastern San Gabriel Mountains, California: Geological Society of America Bull., v. 74, p. 507–512.
Hudson, D. E., 1971. Dynamic properties of full-scale structures determined from natural excitations: Symposium on the dynamic response of structures, Stanford.
Hudson, D. E., *Ed.*, 1971. Strong-motion instrumental data on the San Fernando earthquake of February 9, 1971: Earthquake Engi-

neering Research Laboratory, California Institute of Technology; and Seismological Field Survey, NOAA, 258 p.

Hudson, D. E., and Brady, A. G., 1969. Strong-motion earthquake accelerograms—Digitized and plotted data, 70-20: Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, Report No. EERL 70-20, v. 1, Part A.

Hudson, D. E., Brady, A. G., Trifunac, M. D., and Vijayaraghaven, A., 1971. Strong-motion accelerograms—Digitized and plotted data. Corrected accelerograms and integrated ground velocity and displacement curves: Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, Report No. EERL 71-50, v. II, Part A.

Hudson, D. E., Trifunac, M. D., Brady, A. G., and Vijayaraghaven, A., 1971. Analyses of strong-motion earthquake accelerograms, Response spectra: Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, Report No. EERL 71-80, v. III, Part A.

Hudson, D. E., Trifunac, M. D., Udwadia, F. E., Vijayaraghaven, A., and Brady, A. G., 1971. Analyses of strong-motion earthquake accelerograms, Fourier amplitude spectra: Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, Report No. EERL 71-100, v. IV, Part A.

Hunt, T. M., 1970. Gravity changes associated with the 1968 Inangahua earthquake: New Zealand Journal of Geology and Geophysics, v. 13, no. 4, p. 1050–1051.

Ingram, W. L., 1959. Aliso Canyon oil field: Summary of operations California oil fields, California Division of Oil and Gas, v. 45, no. 1, p. 65–73.

Institute of Governmental Studies, 1971. In the interest of earthquake safety: University of California, Berkeley, 22 p.

Jablonski, H. M., 1970. World relative gravity reference network: U.S. Air Force Aeronautical Chart and Information Center Reference Publication no. 25, approx. 1600 p.

Jahns, R. H., and Muehlberger, W. R., 1954. Geology of the Soledad Basin, Los Angeles County: California Division of Mines Bull. 170, Ch. 1, Map Sheet 6.

Jahns, R. H., Pentegoff, V. P., and Thompson, T. F., 1968. Geologic report on the proposed San Fernando tunnel: Metropolitan Water District of Southern California Report No. 852, 21 p.

Jahns, R. H., Pentegoff, V. P., and Thompson, T. F., 1970. Geologic report on the proposed Sunland No. 1 and Sunland No. 2 tunnels: Metropolitan Water District of Southern California, unpublished report no. 871, 20 p.

Jennings, C. W., and Hart, E. W., 1956. Exploratory wells drilled outside of oil and gas fields in California to December 31, 1953: California Division of Mines Special Report 45.

Jennings, C. W., and Strand, R. G., 1969. Geologic map of California, Olaf P. Jenkins edition, Los Angeles sheet: California Division of Mines and Geology.

Jennings, Paul C., Ed., 1971. Engineering features of the San Fernando earthquake of February 9, 1971: Earthquake Engineering Research Laboratory, California Institute of Technology EERL 71-02, 512 p.

Jennings, R. A., 1957. Geology of the southeastern part of the Oat Mountain quadrangle and adjacent parts of the San Fernando quadrangle, Los Angeles County, California: University of California, Los Angeles, unpublished M.A. thesis, 105 p.

Johnson, D. L., 1967. Caliche on the Channel Islands: California Division of Mines and Geology, Mineral Information Service, v. 20, no. 12, p. 151–158.

Jungels, P., and Anderson, D. L., 1971. Strains and tilts associated with the San Fernando earthquake: U.S. Geological Survey Professional Paper 733, p. 77–79.

Kahle, J. E., Barrows, A. G., Weber, F. H., Jr., and Saul, R. B., 1971. Geologic surface effects of the San Fernando earthquake: California Division of Mines and Geology, California Geology, v. 24, no. 4-5, p. 75–79.

Kamb, Barclay, Silver, L. T., Abrams, M. J., Carter, B. A., Jordan, T. H., and Minster, J. B., 1971. Pattern of faulting and nature of fault movement in the San Fernando earthquake, *in* The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 41–54.

Kew, W. S. W., 1924, Geology and oil resources of part of Los Angeles and Ventura Counties, California: U.S. Geological Survey Bull. 753, 202 p.

King, K. W., 1969. Technical discussions of off-site safety programs for underground nuclear detonations, Chapter 8: Ground motion and structural response instrumentation, U.S. Atomic Energy Commission, Nevada Operations Office, NVO-40 (Revision No. 2).

Koch, Thomas W., 1933. Analysis and effects of current movement on an active fault in Buena Vista Hills oil field, Kern County, California: Bull. American Association of Petroleum Geologists, v. 17, no. 6, p. 694–712.

Kuroiwa, J. H., 1967. Vibration test of a multistory building: Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena.

Lahr, J. C., Wyss, Max, and Hileman, J. A., 1971. Repeated surveys of small-scale figures established across surface fault ruptures following the earthquake, p. 86–88, *in* The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733.

Lane, S. S., 1972. Basic aspects of BPF, PSRV and Fourier Amplitude spectra, Environmental Research Corporation Report, NVO-1163-TM-16 (Revision 1).

La Rue, E. C., 1943. Los Angeles County drainage area, California, Tujunga Wash Improvement, Hansen Dam Geology—areal: Corps of Engineers, U.S. Army.

Lawson, A. C., 1908. The California earthquake of April 18, 1906, Report of the State Earthquake Investigation Commission: Carnegie Institution of Washington Publication 87, v. 1, 451 p.

Leach, E. C., 1948. Geology of Aliso Canyon field, Los Angeles County, California, *in* Structure of typical American oil fields: American Association of Petroleum Geologists, Tulsa, Oklahoma, v. 3, p. 24–38.

Lee, K. L., and Fitton, J. A., 1969. Factors affecting the cyclic loading strength of soil, vibration effects of earthquakes on soils and foundations: American Society for Testing Materials, Stp 450.

Lefter, James, 1971. The impact of the San Fernando earthquake on Veterans Administration facilities and design procedures: Unpublished.

Legge, J. A., Jr., 1937. Geology of a northern portion of the Sunland quadrangle, Los Angeles County: California Institute of Technology, unpublished B.S. thesis, 28 p.

Legislature, State of California, 1970. Joint Committee on Seismic Safety, June 30, 1970, Progress report, 122 p.

Legislature, State of California, 1971. Joint Committee on Seismic Safety, July 31, 1971, Preliminary report on the San Fernando earthquake study, 126 p.

Legislature, State of California, 1971. Joint Committee on Seismic Safety, Earthquake Risk Conference Proceedings, September 22–24, 1971, 152 p.

Legislature, State of California, 1972. Joint Committee on Seismic Safety, July 1972, The San Fernando earthquake of February 9, 1971 and public policy, George O. Gates, Ed., 131 p.

Lofgren, Ben. E., 1966. Tectonic movement in the Grapevine area, Kern County, California: U.S. Geological Survey Professional Paper 550-B, p. B6–B11.

Lomnitz, C., 1966. Magnitude stability in earthquake sequences: Bull. Seismological Society of America, v. 56, p. 247–249.

Long, J. F., and Grannel, R. B., 1971. A detailed gravity survey of the San Gabriel anorthosite body: Geological Society of America, Cordilleran Section, 67th Annual Meeting, Abstracts with programs, v. 3, no. 2, p. 151–152.

Long Beach, City of, 1971. Earthquake hazard regulations for rehabilitation of existing structures within the city: Long Beach Municipal Code, Subdivision 80.

Los Angeles County, March 1972. Reports of the earthquake task forces—concerning the recommendations of the Los Angeles County Earthquake Commission: Los Angeles County Board of Supervisors, 61 p.

Los Angeles County Earthquake Commission, 1971. Report of the Los Angeles Earthquake Commission: Los Angeles County Board of Supervisors, Nov. 1971, 45 p.

Los Angeles County Engineer, Survey Division, in press, 1972. Land movement studies relating to the San Fernando earthquake of February 9, 1971: County of Los Angeles for Subcommittee on Geology, I. H. Alexander, chairman.

Louderback, G. D., 1942. Faults and earthquakes: Bull. Seismological Society of America, v. 32, p. 305.

Madrid, Carlos, 1972. Watermaster service in the upper Los Angeles River area, Los Angeles County, for the period October 1, 1970 through September 30, 1971: California Department of Water Resources Bull. 181-71, 71 p.

Madsen, S. H., and Smith, J. L., 1971. Geologic investigation of earthquake damage, Sylmar High School, conducted for Los Angeles City Unified School District: Fugro, Inc., July 2, 1971, 9 p.

Major, M. W., 1971. Deformation without earthquakes, the central Aleutians: Abstract in Program Cordilleran Section, Geological Society of America 67th Annual Meeting, Riverside, California, p. 154–155.

Mal, A. K., 1972. Rayleigh waves from a moving thrust fault: Bull. Seismological Society of America, v. 62, no. 3, p. 751–762.

Maley, Richard P., 1971. Strong-motion acceleration records from the San Fernando, California, earthquake of February 9, 1971: Association of Engineering Geologists Program, 14th National Meeting, October 19–22, 1971.

Maley, R. P., and Cloud, W. K., 1971. Preliminary strong-motion results from the San Fernando earthquake of February 9, 1971, *in* The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 163–176.

Mansinha, L., and Smylie, D. E., 1971. The displacement fields of inclined faults: Bull. Seismological Society of America, v. 61, p. 1433–1440.

Marachi, N. D., 1972. Dynamic soil problems at the Joseph Jensen Filtration Plant (abstract): Investigations of the San Fernando earthquake, National Conference on Earthquake Engineering, Los Angeles, California, February 7–9, 1972, Program p. 23.

Matuzawa, Takeo, 1964. A study of earthquakes: Uno Shoten, Tokyo, 213 p.

McEvilly, T. V., Bakum, W. H., and Casaday, K. B., 1967. The Parkfield, California, earthquake of 1966: Bull. Seismological Society of America, v. 57, p. 1221–1244.

Meade, B. K., 1963. Horizontal crustal movements in the United States. Report to the Commission on Recent Crustal Movements of the International Association of Geodesy of the International Union of Geophysicists and Geodesists given in Berkeley, California.

Meade, B. K., 1968. Report of the Sub-commission on Recent Crustal Movements in North America: Third Symposium on Recent Crustal Movements of the International Association of Geodesy of the International Union of Geophysicists and Geodisists, Leningrad, USSR.

Meade, B. K., 1970. Horizontal movement along the San Andreas fault system: International Symposium on Recent Crustal Movements and Associated Seismicity, Wellington, New Zealand.

Meade, B. K., and Small, J. B., 1966. Current and recent movement on the San Andreas fault, *in* Geology of northern California: California Division of Mines and Geology Bull. 190, p. 385–391.

Meehan, J. F., 1971. Damage to transportation systems *in* The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 241–244.

Melchior, P. J., 1966. The earth tides: Pergamon Press, New York, 458 p.

Mellmon, G. R., 1972. Seismic observations and their tectonic implications for the Pacific-North American plate boundary: Geological Society of America Cordilleran Section 68th Annual Meeting, Abstracts with programs, v. 4, no. 3, p. 198.

Menard, H. W., 1955. Deformation of the northeastern Pacific basin and the west coast of North America: Geological Society of America Bull., v. 66, p. 1149–1198.

Mendenhall, W. C., 1908. Ground water and irrigation enterprises in the Foothill Belt, southern California: U.S. Geological Survey Water Supply Paper 219.

Merifield, P. M., 1958. Geology of a portion of the southwestern San Gabriel Mountains, San Fernando and Oat Mountain quadrangles, Los Angeles County, California: University of California, Los Angeles, unpublished M.A. thesis, 61 p.

Miller, W. J., 1928. Geomorphology of the southwestern San Gabriel Mountains of California: University of California Department of Geological Sciences, Bull., v. 17, p. 193–240.

Miller, W. J., 1931. Anorthosite in Los Angeles County, California: Journal of Geology, v. 39, p. 331–344.

Miller, W. J., 1934, Geology of the western San Gabriel Mountains of California: University of California, Publications in Mathematics and Physical Science, v. 1, no. 1, p. 1–114.

Miller, Robert W., et al., 1969. Crustal movement investigations—triangulation, Taft-Mojave area, California: U.S. Coast and Geodetic Survey Operational Data Report DR-5.

Miller, Robert W., et al., 1969. Crustal movement investigations—triangulation, Taft-Mojave area, California: U.S. Coast and Geodetic Survey, Operational Data Report DR-6.

Miller, Robert W., et al., 1970. Crustal movement investigations—triangulation, Part I, Imperial Valley, Vicinity of El Centro, and Part II, Anza-Borrego Desert area, California: U.S. Coast and Geodetic Survey Operational Data Report DR-10.

Mitchell, R. J., 1971. Survey requirements imposed by earthquakes, *in* Papers from the 1971 ASP-ACSM fall convention, American Congress on Surveying and Mapping, September 7–11, 1971, San Francisco, California: paper 71–390, p. 131–147.

Morrill, B. J., 1971. Evidence of record vertical accelerations at Kagel Canyon during the earthquake, *in* The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 177–181.

Morton, D. M., 1971a. Seismically triggered landslides above San Fernando Valley: California Division of Mines and Geology, California Geology, v. 24, no. 4-5, p. 80–82

Morton, D. M., 1971b. Seismically triggered landslides in the area above San Fernando Valley, *in* The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 99–104.

Morton, D. M., 1971c. Geology of parts of the Azusa and Mount Wilson quadrangles, San Gabriel Mountains, Los Angeles County, California: California Division of Mines and Geology Map Sheet 18.

Morton, D. M., and Streitz, R., 1969. Preliminary reconnaissance map of major landslides, San Gabriel Mountains, California: California Division of Mines and Geology Map Sheet 15.

Muehlberger, W. R., 1965. Late Paleozoic movement along the Texas lineament: Transactions New York Academy of Sciences Ser. II, v. 27, p. 385–392.

Murphy, J. R., and Davis, A. H., 1969. Amplification of Rayleigh waves in a surface layer of variable thickness: Environmental Research Corporation Report, NVO-1163-175.

Murphy, J. R., Davis, A. H., and Weaver, N. L., 1971. Amplification of seismic body waves by low-velocity surface layers: Bull. of the Seismological Society of America, v. 61, no. 11, pp. 109–145.

Muto, Kiyoshi, 1971. Strong-motion records and simulation analysis of K11 Building in San Fernando earthquake: Muto Institute of Structural Mechanics, Tokyo, Report 71-2-1.

Nagle, H. E., and Parker, E. S., 1971. Future oil and gas potential of onshore Ventura basin, California, p. 254–297, *in* Cram, I. H., Future petroleum provinces of the United States—their geology and potential: American Association of Petroleum Geologists Memoir 15, v. 1, 803 p.

Nason, R. D., 1969. Continuing fault movement after earthquakes: American Geophysical Union Transactions, v. 50, no. 4, p. 252.

Nason, R. D., 1971a. Instrumental monitoring of post-earthquake fault movements, p. 89–90, *in* The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733.

Nason, Robert D., 1971b. Investigation of fault creep slippage in northern and central California: unpublished Ph.D. thesis.

Nason, R. D., 1971c. Shattered earth at Wallaby Street, Sylmar, in The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 97–98.

National Academy of Sciences, 1969. Seismology—Responsibilities and requirements of a growing science: National Academy, Washington, D.C., Part I, 38 p., Part II, 59 p.

National Academy of Sciences, 1969. Toward reduction of losses from earthquakes—Conclusions from the great Alaska earthquake of 1964, 34 p.

National Academy of Sciences, in press, 1971. Research on earthquake modification, Panel on Earthquake Modification: U.S. National Committee for Rock Mechanics Report.

National Academy of Sciences—National Academy of Engineering, 1971. The San Fernando earthquake of February 9, 1971: Lessons from a moderate earthquake on the fringe of a densely populated region, 24 p.

National Oceanic and Atmospheric Administration, 1971. San Fernando, California, earthquake of February 9, 1971: Natural Disaster Survey Report 71-1, 15 p.

National Transportation Safety Board, 1972. Protection of transportation facilities against earthquakes: National Transportation Safety Board, Washington, D.C., Rpt. No. NTSB-STS-72-1.

Neuerberg, G. J., 1953. Geology of the Griffith Park area, Los Angeles County, California: California Division of Mines Special Report 33.

Nolte, C. B., 1937. Structure and stratigraphy of a portion of San Gabriel Foothills in the northern third of the Sunland quadrangle, Los Angeles County, California: California Institute of Technology, Pasadena, unpublished B.S. thesis, 42 p.

Oakeshott, G. B., 1937. Geology and mineral deposits of the western San Gabriel Mountains, Los Angeles County: California Division of Mines, California Journal of Mines and Geology, v. 33, no. 3, p. 215–249.

Oakeshott, G. B., 1952. Geology of the northern margin of the San Fernando Valley: Petroleum World, v. 49, no. 1, p. 20-24.

Oakeshott, G. B., 1954. Geology of the western San Gabriel Mountains, Los Angeles County, in Jahns, R. H., ed., Geology of southern California: California Division of Mines Bull. 170, map sheet 9.

Oakeshott, G. B., ed., 1955. Earthquakes in Kern County, California, during 1952: California Division of Mines Bull. 171, pp. 15–22.

Oakeshott, G. B., 1958. Geology and mineral deposits of San Fernando quadrangle, Los Angeles County, California: California Division of Mines Bull. 172, 147 p.

Oakeshott, G. B., Greensfelder, R. W., and Kahle, J. E., 1972. One hundred years later (Owens Valley earthquake of 1872): California Division of Mines and Geology, California Geology, March 1972, p. 56–61.
Oldham, R. D., 1899. Report on the great earthquake of 12th June 1897: Geological Survey of India Memoirs, v. 29, 379 p.
Oliver, H. W., 1960. Gravity anomalies at Mt. Whitney, California: U.S. Geological Survey Professional Paper 400B, p. 313–315.
Oliver, H. W., 1965. The U.S. Geological Survey's gravity program in California, Hawaii, Nevada, and Oregon: American Geophysical Union Transactions, v. 46, no. 1, p. 218–222.
Oliver, H. W., 1969. The U.S. Geological Survey's gravity programs in California: EOS, v. 50, no. 10, p. 543–545.
Orlin, Hyman, 1966. Gravity surveys *in* ESSA symposium on earthquake prediction, Rockville, Maryland, 1966: U.S. Government Printing Office, Washington, D.C., p. 128–130.
Palmer, D. F., and Henyey, T. L., 1971. San Fernando earthquake of 9 February 1971: Pattern of faulting: Science, 14 May 1971, p. 712–715.
Paschall, R. H., and Off, Theodore, 1961. Dip-slip versus strike-slip movement on San Gabriel fault, southern California: American Association of Petroleum Geologists Bull., v. 45, p. 1941–1956.
Pecora, William T., Chairman, Interagency Working Group for Earthquake Research, Federal Council for Science and Technology, 1968. Proposal for a Ten-Year national earthquake hazards program: Office of Science and Technology, 81 p.
Press, F., 1960. Crustal structure in the California-Nevada region: Journal of Geophysical Research, v. 65, p. 1039–1051.
Press, Frank, Chairman, 1965. Earthquake prediction: A proposal for a ten-year program of research, *Ad* hoc Panel on Earthquake Prediction: Office of Science and Technology.
Proctor, R. J., 1968. Geologic map and section along the 5.5-mile San Fernando Tunnel: Unpublished map no. L-1078 by the Metropolitan Water District of Southern California (Revised February 26, 1971, by MWD).
Proctor, R. J., 1972. Known faults, surface ruptures, and fluctuations of groundwater levels (abstract): Earthquake Engineering Research Institute, National Conference on Earthquake Engineering, Los Angeles, Feb. 7–9, 1972.
Proctor, R. J., Brooks, D. C., and Pentegoff, V. P., 1966. Exploration for 52 miles of tunnel for the Foothill feeder, p. 81–87 *in* Lung, R. and Proctor, R. J. (eds.) Engineering geology in southern California: Association of Engineering Geologists, Box 1242, Arcadia, California, 386 p.
Proctor, R. J., Crook, R., Jr., McKeown, M. H., and Moresco, R. L., 1972. Relation of known faults to surface ruptures, 1971 San Fernando earthquake, southern California: Geological Society of America Bull., v. 83, no. 6, p. 1601–1618.
Proctor, R. J., Payne, C. M., and Kalin, D. C., 1970. Crossing the Sierra Madre fault zone in the Glendora Tunnel, San Gabriel Mountains, California: Engineering Geology (Elsevier), v. 4, no. 1, p. 5–63.
Radbruch, D. G., and Bonilla, M. G., 1966. Tectonic creep in the Hayward fault zone, California: U.S. Geological Survey Circular 525.
Raleigh, C. B., and Burford, R. O., 1969. Tectonics of the San Andreas fault system, strain studies: Transactions American Geophysical Union, v. 50, no. 5, p. 380–381.
Ransome, F. L., 1915. The Tertiary orogeny of the North American Cordillera and its problems, *in* W. N. Rice et al., Problems of American Geology, New Haven, p. 287–376.
Reid, H. F., 1910. The mechanics of the earthquake, *in* the California earthquake of April 18, 1906, Report of the State Earthquake Investigation Commission, V. II: Carnegie Institution of Washington (Reprinted 1969).
Resources Agency, State of California, 26 April 1967. Earthquake and geologic hazards in California—A report to the Resources Agency by the Geologic Hazards and Advisory Committees for Program and Organization, 18 p.
Rice, D. A., 1969. Gravity observations in Alaska, 1964–65, including some repeat observations, p. 5–20, *in* Leopold, L. E. (Ed.), The Prince William Sound, Alaska, earthquake of 1964 and aftershocks v. 3: U.S. Coast and Geodetic Survey Publication, 10-3, 161 p.
Richardson, Lorie, 1972. Left-lateral, east-trending faults in the Alabama Hills (Owens Valley, California): California Division of Mines and Geology, California Geology, March 1972, p. 62–64.
Richter, C. F., 1958. Elementary seismology: W. H. Freeman and Co. San Francisco, 768 p.
Rietman, J. D., 1969. Gravity surveys in the western Transverse Range Province, California: EOS, v. 50, no. 10, p. 545–546.
Robbins, S. L., Grannell, R. V., Alewine, R. W., Biehler, Shawn, and Oliver, H. W., 1972. Descriptions, sketch maps, and selected pictures of 88 gravity stations reoccupied after the San Fernando earthquake of February 9, 1971: U.S. Geological Survey open-file report, 72 p.
Rogers, T. H., 1965. Geologic map of California, Olaf P. Jenkins Edition, Santa Ana sheet: California Division of Mines and Geology.
Rogers, T. H., 1967. Geologic map of California, Olaf P. Jenkins Edition, San Bernardino sheet: California Division of Mines and Geology.
Roller, J. C., and Healy, J. H., 1963. Seismic refraction measurements of crustal structures between Santa Monica Bay and Lake Mead: Journal of Geophysical Research, v. 68, no. 20, p. 5837–5849.
Roth, G. H., and Sullwold, H. H., Jr., 1962. Cascade oil field: American Association of Petroleum Geologists Pacific Section, Spring Field Trip, Guidebook, p. 13–14.
Saint-Amand, Pierre, 1961. Los Terremotos de Mayo—Chile, 1960: U.S. Naval Ordnance Test Station, China Lake, Technical Article 14, TP 2701, 39 p.
Saul, R. B., 1971. Geology of west central part of the Mount Wilson quadrangle: California Division of Mines and Geology, unpublished mapping.
Savage, J. C., 1971a, Land deformations resulting from the San Fernando earthquake, *in* Papers from the 1971 ASP-ACSM fall convention, American Congress on Surveying and Mapping, September 7–11, 1971, San Francisco, California: paper 71-387, p. 112–120.
Savage, James C., 1971b. The absence of conclusive proof for strain accumulation in the San Francisco Bay area: Transactions American Geophysical Union, v. 52, no. 11, p. 815.
Savage, J. C., and Burford, R. O., 1970. Accumulation of tectonic strain in California: Bull. Seismological Society of America, v. 60, no. 6, p. 1877–1896.
Savage, J. C., and Burford, R. O., 1971. Discussion of paper by C. G. Scholz and T. J. Fitch "Strain accumulation along the San Andreas fault": Journal of Geophysical Research, v. 76, no. 6, p. 6469–6479.
Savage, J. C., and Hastie, L. M., 1969. A dislocation model for the Fairview Peak, Nevada, earthquake: Bull. Seismological Society of America, v. 59, p. 1937–1948.
Schoellhamer, J. E., Vedder, J. G., and Yerkes, R. F., 1954. Geology of the Los Angeles Basin: California Division of Mines Bull. 170, Chap. 2, plate 1.
Scholz, C. H., and Fitch, Thomas J., 1969. Strain accumulation along the San Andreas fault: Journal of Geophysical Research, v. 74, no. 27, p. 6649–6666.
Scholz, C. H., and Fitch, Thomas J., 1970. Strain and creep in central California: Journal of Geophysical Research, v. 75, no. 23, p. 4447–4453.
Scholz, C. H., 1971. Rock mechanics and dynamic processes in the crust: Transactions American Geophysical Union, v. 52, no. 5, International Union of Geodesy and Geophysics, IUGG 126–130.
Scholz, C. H., Wyss, Max, and Smith, S. W., 1969. Seismic and aseismic slip on the San Andreas fault: Journal of Geophysical Research, v. 74, no. 8, p. 2049–2069.
Schultz, A., 1967. Magnification of Love waves: Environmental Research Corporation Report, NVO-1163-80.
Schwimmer, P. M., and Rice, D. A., 1969. U.S. national gravity base net: American Geophysical Union EOS, v. 50, no. 10, p. 527–528.
Scott, John D., and Carville, Chester A., 1971. Foundation damage to transmission-line towers during the San Fernando earthquake of February 9, 1971 (abstract): Association of Engineering Geologists Program, 14th National Meeting, October 19–22, 1971.
Scott, J. D., and Schoustra, J. J., 1971. Geologic investigation of earthquake damage, Van Gogh Street School, conducted for Los Angeles City Unified School District: Fugro, Inc., March 25, 1971, 10 p.
Scott, Nina H., 1971. Preliminary report on felt area and intensity, *in* Preliminary report on the San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 153–154.
Scott, R. F., 1971. San Fernando earthquake, 9 February 1971, preliminary soil engineering report, *in* Jennings, P. C., *ed.*, Engineering features of the San Fernando earthquake of February 9, 1971s Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, EERL report 71-02, p. 299–331.
Scott, R. F., in press, 1972. The calculation of horizontal acceleration components from seismoscope records: Bull. Seismological Society of America.
Scott, Stanley, April 26, 1972. Towards a partnership for seismic safety: University of California Institute of Governmental Studies, 22 p., plus Appendix 1–8. Unpublished report.
Seed, H. Bolton, and Idriss, I. M., 1967. Analysis of soil liquefactions Niigata earthquake: Journal of the Soil Mechanics and Foundation

Division, American Society of Civil Engineers, v. 93, no. SM 3, Proceedings Paper 4233, p. 83–108.

Seed, H. Bolton, and Idriss, I. M., 1970. A simplified procedure for evaluating soil liquefaction potential: Earthquake Engineering Center Report No. EERC 70-9, University of California, Berkeley.

Seed, H. B., and Idriss, I. M., 1971. Simplified procedure for evaluating soil liquefaction potential: Journal of Soil Mechanics and Foundation Division, American Society of Civil Engineers, v. 97, no. SM 9, September 1971, p. 1249–1273.

Seed, H. Bolton, and Peacock, W. H., 1970. Applicability of laboratory test procedures for measuring soil liquefaction characteristics under cyclic loading: Earthquake Engineering Research Center Report No. EERC 70-8, University of California, Berkeley, November.

Seismological Society of America, 1971. San Fernando earthquake of February 9, 1971—Preliminary report: Bull. of the Seismological Society of America, v. 61, no. 2, p. 491–510.

Sharp, R. P., 1934. Geology of the Tujunga area, southwestern San Gabriel Mountains, California: California Institute of Technology, Pasadena, unpublished B.S. thesis, 69 p.

Sharp, R. V., 1967. San Jacinto fault zone in the Peninsular Ranges of southern California: Geological Society of America Bull. v. 78, p. 705–730.

Shelton, J. S., 1955. Glendora volcanic rocks, Los Angeles basin, California: Geological Society of America Bull., v. 66, p. 45–90.

Silver, L. T., 1971. Problems of crystalline rocks of the Transverse Ranges: Geological Society of America Abstracts: Cordilleran Section meeting, Riverside, California, p. 193–194.

Silver, L. T., McKinney, C. R., Deutsch, S., and Bolinger, J., 1960. Precambrian age determinations of some crystalline rocks of the San Gabriel Mountains of southern California: Journal of Geophysical Research, v. 65, p. 2522–2523.

Silver, L. T., et al., 1963. Precambrian age determinations in the western San Gabriel Mountains, California: Journal of Geology, p. 196–214.

Slack, K. V., 1967. Physical and chemical description of Birch Creek, a travertine depositing stream, Inyo County, California: U.S. Geological Survey Professional Paper 549-A, 19 p.

Slosson, J. E., 1971. Engineering geology review of Olive View Medical Center and Engineering geology review of Camp Holton, Little Tujunga Canyon, *in* Report on Olive View Hospital: Structural Engineers Association of Southern California, Exhibit D.

Slosson, J. E., and Barnhart, J. T., 1967. Late Pleistocene deformation in the Limekiln Canyon area, Santa Susana Mountains: Southern California Academy of Sciences Bull., v. 66, no. 2, p. 129–134.

Smith, J. L., and Fallgren, R. B., 1972. Ground displacement at San Fernando Juvenile Hall (abstract): Investigations of the San Fernando earthquake, National Conference on Earthquake Engineering, Los Angeles, California, February 7–9, 1972, program, p. 22.

Smith, S. W., and Wyss, Max, 1968. Displacement on the San Andreas fault subsequent to the 1966 Parkfield earthquake: Bull. Seismological Society of America, v. 58, no. 6, p. 1955–1973.

Steinbrugge, Karl V., 1968. Earthquake hazard in the San Francisco Bay area—A continuing problem in public policy: Institute of Governmental Studies, University of California, Berkeley, 80 p.

Steinbrugge, K. V., 1970. Engineering aspects of the Santa Rosa, California, earthquakes, October 1, 1969, *in* The Santa Rosa earthquakes of October 1, 1969: Environmental Science Services Administration.

Steinbrugge, K. V., Chairman, Task Force on Earthquake Hazard Reduction, September 1970: Executive Office of the President, Office of Science and Technology, 54 p. Superintendent of Documents, Washington, D.C.

Steinbrugge, K. V., Schader, E. E., Bigglestone, H. C., and Weers, C. A., 1971. San Fernando earthquake, February 9, 1971: Pacific Fire Rating Bureau, San Francisco, California.

Steinbrugge, K. V., and Zacher, E. G., 1960. Creep on the San Andreas fault: Fault creep and property damage: Bull. Seismological Society of America, v. 50, no. 3, p. 389–396.

Stewart, R. D., 1962. Horse Meadows Oil field: American Association of Petroleum Geologists, Pacific Section, Spring Field Trip Guidebook, p. 6–8.

Structural Engineers Association of Southern California, 1971. Report on Olive View Hospital, San Fernando, California, earthquake of February 9, 1971: 30 p.

Susuki, Takeo, 1952. Stratigraphic paleontology of the type section of the Topanga Formation, Santa Monica Mountains, California (abstract): Geological Society of America Bulletin, v. 63, no. 21, pt. 2, p. 1345.

Talwanis, Manik, Worzel, J. L., and Landisman, Mark, 1959. Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone: Journal Geophysical Research, v. 64, no. 1, p. 49–59.

Taylor, N. Gregory, Robinson, James W., and McKnight, Thomas E., 1972. Earthquakes and title boundaries: Los Angeles Bar Bull., Feb. p. 137–144.

Thayer, W. N., 1945. A resumé of present knowledge of ground water conditions in the vicinity of Hansen spreading grounds: Los Angeles County Flood Control District, Interdepartmental Report.

Tocher, Don, 1960. Creep on the San Andreas fault; Creep rate and related measurements at Vineyard, California: Bull. Seismological Society of America, v. 50, no. 3, p. 396–404.

Townley, S. D., and Allen, M. W., 1939. Descriptive catalog of earthquakes of the Pacific Coast of the United States, 1769 to 1928: Bull. of the Seismological Society of America, v. 29, no. 1, p. 1–252.

Trifunac, M. D., 1971. Zero baseline corrections of strong-motion accelerograms: Bull. Seismological Society of America, v. 61, no. 5, p. 1201–1211.

Trifunac, M. D., 1970. Low-frequency digitization errors and a new method for zero baseline correction of strong-motion accelerograms: Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, Report No. EERL 70-07.

Trifunac, M. D., 1972. Stress estimates for the San Fernando, California, earthquake of February 9, 1971: Main event and thirteen aftershocks: Bull. Seismological Society of America, v. 62, no. 3, p. 721–750.

Trifunac, M. D., and Hudson, D. E., 1970. Laboratory evaluations and instrument corrections of strong-motion accelerographs: Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, Report No. EERL 70-04.

Trifunac, M. D., and Hudson, D. E., 1971. Analysis of the Pacoima Dam accelerograms—San Fernando, California, earthquake of 1971: Bull. Seismological Society of America, v. 61, no. 5, p. 1393–1411.

Trifunac, M. D., Udwadia, F. E., and Brady, A. G., 1971. High-frequency errors and instrument corrections of strong-motion accelerograms: Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, Report No. EERL 71-05.

Udias, A., S.J., 1965. A study of the aftershocks and focal mechanisms of the Salinas-Watsonville earthquakes of August 31 and September 14, 1963: Bull. Seismological Society of America, v. 55, p. 85–106.

Union Oil Company, 1953. Geologic map of a portion of the San Fernando-San Gabriel Foothill belt, Los Angeles County, California: Unpublished map and cross sections by Q. R. Query, R. D. Stewart, G. L. Quick, and H. H. Lian, modifying original work by J. C. Hazzard.

U.S. Coast and Geodetic Survey Building Period Reports: Seismological Field Survey, Department of Commerce, Washington, D.C.

U.S. Department of Agriculture, 1919. Soil survey of the Los Angeles area.

U.S. Department of Agriculture, 1915. Soil map, California, San Fernando Valley sheet: Soil Conservation Service, Washington, D.C.

U.S. Geological Survey (many authors), 1971. The San Fernando, California, earthquake of February 9, 1971: A preliminary report published jointly by the U.S. Geological Survey and the National Oceanic and Atmospheric Administration: U.S. Geological Survey Professional Paper 733, 254 pp.

U.S. Geological Survey, 1971. Surface faulting, *in* The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 55–76.

Vacquier, Victor, Raff, A. D., and Warren, R. E., 1961. Horizontal displacements in the floor of the northeastern Pacific Ocean: Geological Society of America, Bull., v. 72, p. 1251–1258.

von Huene, Roland, 1969. Geologic structure between the Murray fracture zone and the Transverse Ranges: Marine Geology, v. 7, p. 475–499.

von Huene, Roland, 1971. A possible relationship between the Transverse Ranges of California and the Murray fracture: Geological Society of America Abstract: Cordilleran Section meeting, Riverside, California, p. 213.

Wallace, R. E., and Roth, E. F., 1967. Rates and patterns of progressive deformation, p. 23–40, *in* The Parkfield-Cholame, California, earthquakes of June–August 1966: U.S. Geological Survey Professional Paper 579.

Warrick, R. E., and Joyner, W. B., 1971. Preliminary results from recording aftershock ground motion on alluvial deposits *in* The San

Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 91–96.

Watson, James P., 1972. Impairment of purchase-money security by disaster and the antideficiency legislation: The sounds of silence: Los Angeles Bar Bull., Feb., p. 146–153.

Weigel, R. L., ed., 1970. Earthquake engineering: Prentice-Hall, Inc., Englewood Cliffs, N.J.

Weldon, John, Jr., 1955. Geology of the Pasadena-Eagle Rock area: Claremont College unpublished master's thesis.

Wentworth, C. M., and Yerkes, R. F., 1971. Geologic setting and activity of faults in the San Fernando area, California: U.S. Geological Survey Professional Paper 733, p. 6–16.

Wentworth, C. M., Ziony, J. I., and Buchanan, J. M., 1970. Preliminary geologic environmental map of the greater Los Angeles area, California: U.S. Geological Survey, TID-25363, 41 p.

Wesson, R. L., and Gibbs, J. F., 1971. Crustal structure in the vicinity of the San Fernando, California, earthquake of 9 February 1971 (abstract): American Geophysical Union Transactions, v. 52, p. 864.

Wesson, R. L., Lee, W. H. K., and Gibbs, J. F., 1971. Aftershocks of the earthquake *in* U.S. Geological Survey Professional Paper 733, p. 24–29.

Whitcomb, J. H., 1971a. Fault-plane solutions of the February 9, 1971, San Fernando earthquake and some aftershocks: U.S. Geological Survey Professional Paper 733, p. 30–32.

Whitcomb, J. H., 1971b. Focal mechanisms of the San Fernando aftershock series (abstract): American Geophysical Union Transactions, v. 52, p. 862–863.

White, W. S., 1937. Geology of the Pacoima-Little Tujunga area: California Institute of Technology, Pasadena, unpublished M. S. thesis, 42 p.

Whitman, Robert V., 1970. Hydraulic fills to support structural loads: Journal Soil Mechanics and Foundation Division, American Society of Civil Engineers, v. 96, no. SM 1, Proceedings Paper 7009, p. 23–47.

Whitten, C. A., 1971. Crustal-movement surveys and pre-earthquake strain analysis, *in* The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 161–162.

Whitten, C. A., and Claire, C. N., 1960. Creep on the San Andreas fault: Analysis of geodetic measurements along the San Andreas fault: Bull. Seismological Society of America, v. 50, no. 3, p. 404–415.

Winterer, E. L., and Durham, D. L., 1954. Geology of a part of the eastern Ventura Basin, Los Angeles County, *in* Johns, R. H., ed., Geology of southern California: California Division of Mines Bull. 170, map sheet 5.

Winterer, E. L., and Durham, D. L., 1958. Geologic map of a part of Ventura Basin, Los Angeles County: U.S. Geological Survey, Oil and Gas Investigations Map OM 196.

Winterer, E. L., and Durham, D. L., 1962. Geology of southeastern Ventura Basin, Los Angeles County, California: U.S. Geological Survey Professional Paper 334-H, p. 275–336.

Wood, M. D., Allen, R. V., and Levine, S. R., 1971. Anomalous microtilt preceding a local earthquake: Bull. Seismological Society of America, v. 61, no. 6, p. 1801–1809.

Woollard, G. P., 1964. An analysis of the reliability of gravimeter measurements: Hawaii Institute of Geophysics Report 64-9 (AFCRL-64-771), 50 p.

Wyss, Max, and Brune, J. N., 1971. Regional variations of source parameters in southern California estimated from the ratio of short-to-long-period amplitudes: Bull. Seismological Society America, v. 61, no. 5, p. 1153–1168.

Wyss, Max, and Hanks, T. C., 1972. The source parameters of the San Fernando earthquake inferred from teleseismic body waves: Bull. Seismological Society America, v. 62, no. 2, p. 591–602.

Yerkes, R. F., in press 1973. Effects of the earthquake as related to geology: Earthquake Engineering Research Institute—National Ocean and Atmospheric Administration special volume on the San Fernando earthquake.

Yerkes, R. F., and Campbell, R. H., 1971. Cenozoic evolution of the Santa Monica Mountains-Los Angeles basin area: I. Constraints on tectonic models: Geological Society America, Abstract, Cordilleran Section meeting, Riverside, California, p. 222.

Yerkes, R. F., McCulloh, T. H., Schoellhamer, J. E., and Vedder, J. G., 1965. Geology of the Los Angeles basin, California—an introduction: U.S. Geological Survey Professional Paper 420-A, 57 p.

Youd, T. L., 1971. Landsliding in the vicinity of the Van Norman Lakes, in The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 105–109.

Youd, T. L., 1972. Landslides in the vicinity of the Van Norman Lakes (abstract): Investigations of the San Fernando earthquake, National Conference on Earthquake Engineering, Los Angeles, California, February 7–9, 1972, program, p. 21.

Youd, T. L., and Olsen, H. W., 1971. Damage to constructed works, associated with soil movements and foundation failures, *in* The San Fernando, California, earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 126–132.

INDEX

STAFF ASSISTANCE FOR THIS BULLETIN WAS PROVIDED BY:

Wilma L. Ashby, *typing*

Richard T. Boylan, *cartography, design*

Mary Louise Burgess, *typing*

Sharon Burton, *typing*

Darris Campbell, *typing*

Marilyn Daytan, *copy editing and typography*

Dorothy Y. Fong, *cartography*

Edward L. Foster, *cartography, design*

Mary Hill, *editorial supervision*

Carl Hauge, *editing*

Venice Huffman, *typing*

Elizabeth Lindgren, *cartography*

Ron Morgan, *cartography*

Vivian Muston, *cartography, design*

R. Merl Smith, *publication supervision*

Jeffrey O. Tambert, *cartography*

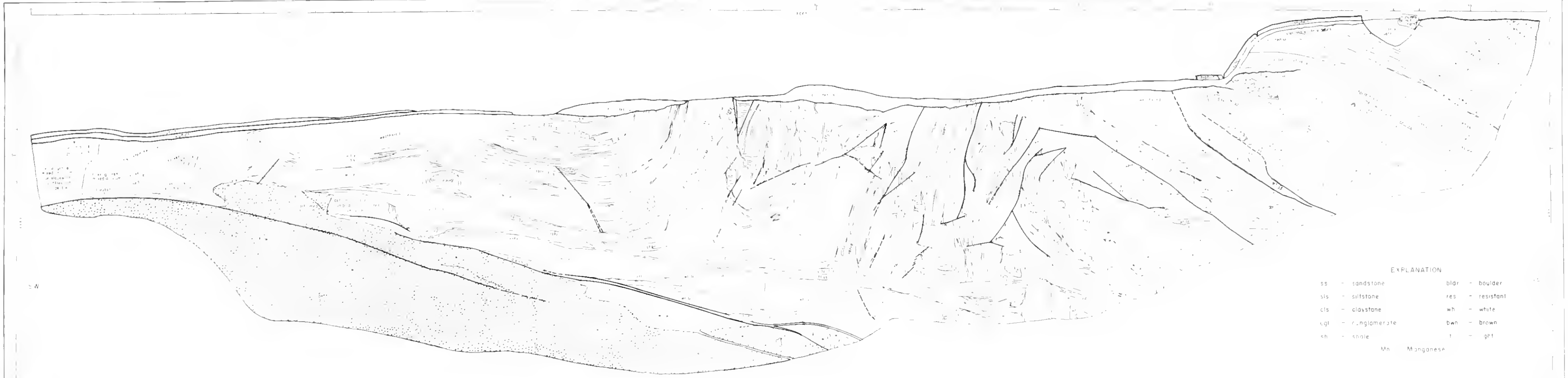
Margaret W. Turner, *typing*

86424—650 6/74 6M

SAN FERNANDO EARTHQUAKE
BULLETIN 196, PLATE 1

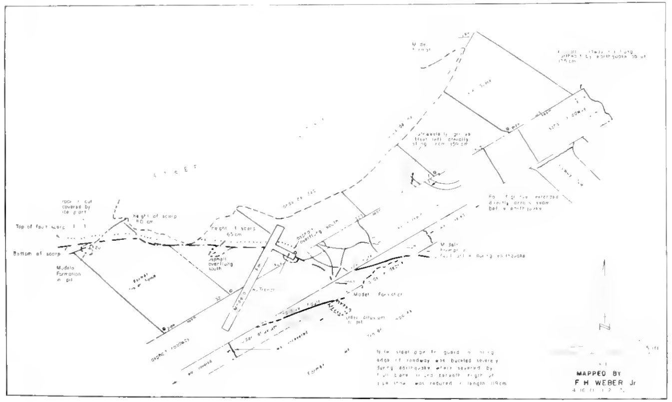
EXPLANATION

Qs — Dune sand



EXPLANATION

ss	sandstone	bldr	boulder
sls	siltstone	res	resistant
cls	claystone	wh	white
cgl	conglomerate	bwn	brown
sh	shale	lt	light
Mn	Manganese		



Map of Surface Effects and Location of Trench in Blue Star Trailer Park

GEOLOGIC SECTION ACROSS SAN FERNANDO EARTHQUAKE FAULT SCARP EXPOSED IN TRENCH NEAR MOUTH OF LOPEZ CANYON

BY
A G BARROWS and J E KAHLE
CALIFORNIA DIVISION OF MINES AND GEOLOGY
APRIL 1971

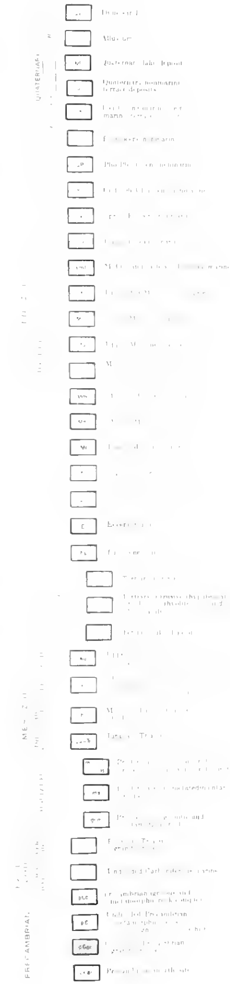
SYMBOLS

Fault, active during earthquake
Fault, inactive during earthquake, dashed where not perfectly exposed

CALIFORNIA DIVISION OF MINES AND GEOLOGY
WESLEY G. BRUER, STATE GEOLOGIST

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF CONSERVATION

EXPLANATION



TOPOGRAPHIC BASE MAP

Minor corrections and additions to culture by California Division of Mines and Geology 1969

Land net prepared by U.S. Geological Survey

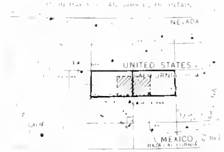
Contact

Fault

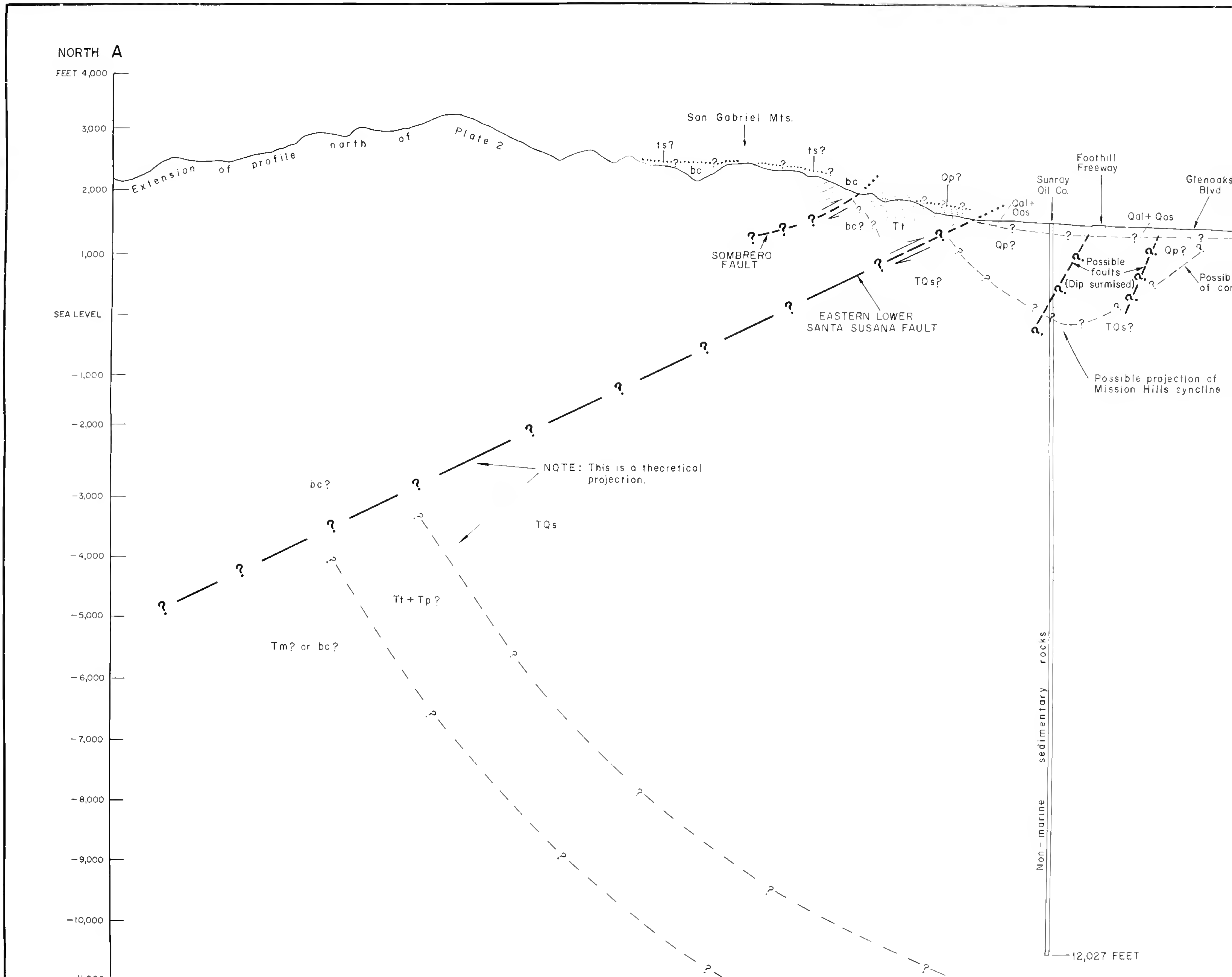
Thrust fault

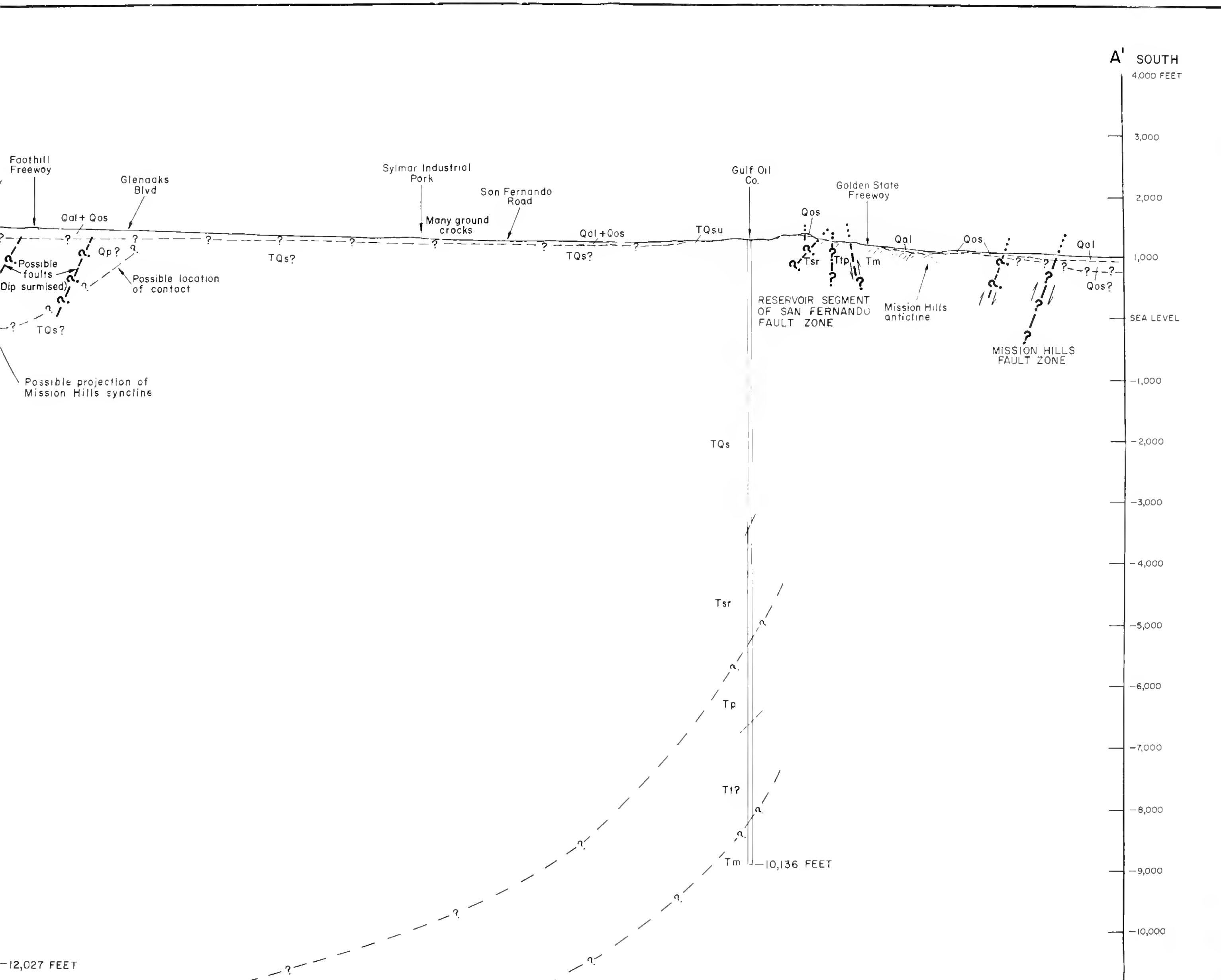
Scale 1:250,000

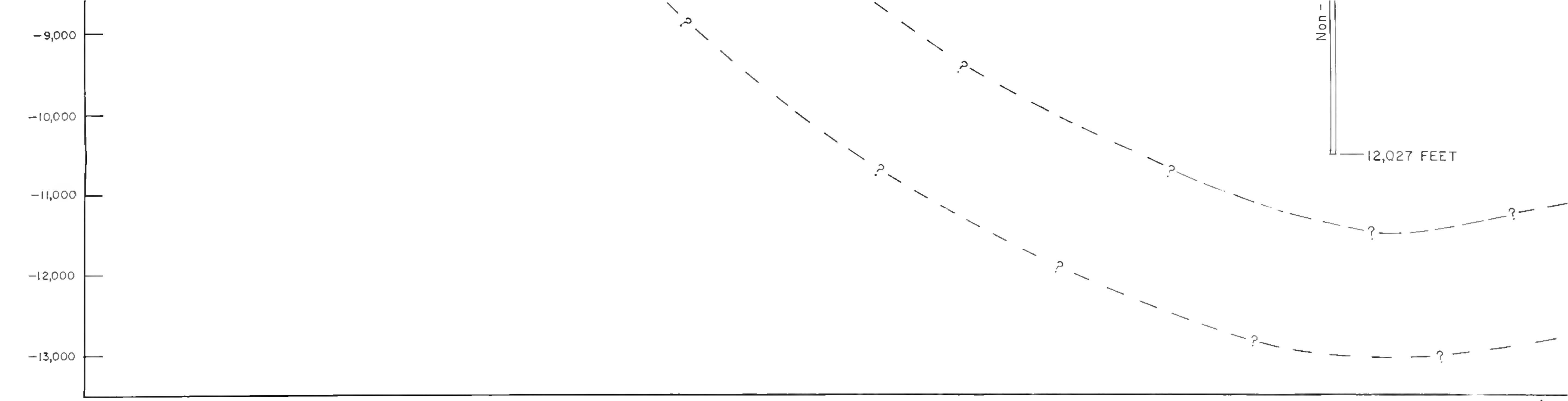
CONTOUR INTERVAL 200 FEET
WITH SUPPLEMENTARY CONTOURS AT 100 FOOT INTERVALS



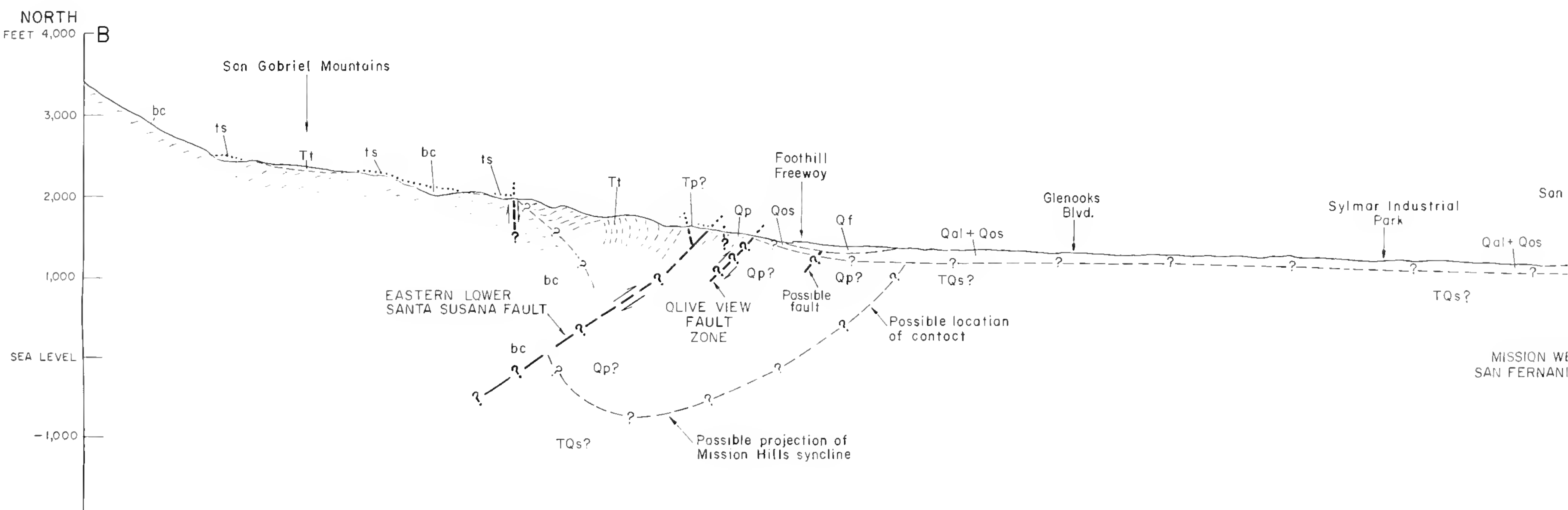
GEOLOGIC MAP OF THE SAN GABRIEL MOUNTAINS, CALIFORNIA


NORTH A
FEET 4,000
3,000
2,000
1,000
SEA LEVEL
-1,000
-2,000
-3,000
-4,000
-5,000
-6,000
-7,000
-8,000
-9,000
-10,000
Extension of profile north of Plate 2
San Gabriel Mts.
ts?
bc
Qp?
Sunray Oil Co.
Foothill Freeway
Glenaoks Blvd
Qal + Qos
Qal + Qos
bc?
Tt
Qp?
SOMBRERO FAULT
TQs?
Possible faults (Dip surmised)
EASTERN LOWER SANTA SUSANA FAULT
TQs?
Possible projection of Mission Hills syncline
NOTE: This is a theoretical projection.
bc?
TQs
Tt + Tp ?
Tm? or bc?
Non-marine sedimentary rocks
12,027 FEET


A'
SOUTH
4,000 FEET
3,000
2,000
1,000
SEA LEVEL
−1,000
−2,000
−3,000
−4,000
−5,000
−6,000
−7,000
−8,000
−9,000
−10,000
Foothill Freeway
Glenoaks Blvd
Sylmar Industrial Park
Many ground cracks
San Fernando Road
Gulf Oil Co.
Golden State Freeway
Qal + Qos
Qp?
TQs?
Possible faults
(Dip surmised)
Possible location of contact
Possible projection of Mission Hills syncline
Qal + Qos
TQsu
Qos
Tsr
Ttp
Tm
Qal
Qos
Qal
Qos?
RESERVOIR SEGMENT OF SAN FERNANDO FAULT ZONE
Mission Hills anticline
MISSION HILLS FAULT ZONE
TQs
Tsr
Tp
Tt?
Tm
10,136 FEET
12,027 FEET



SECTION A-A'

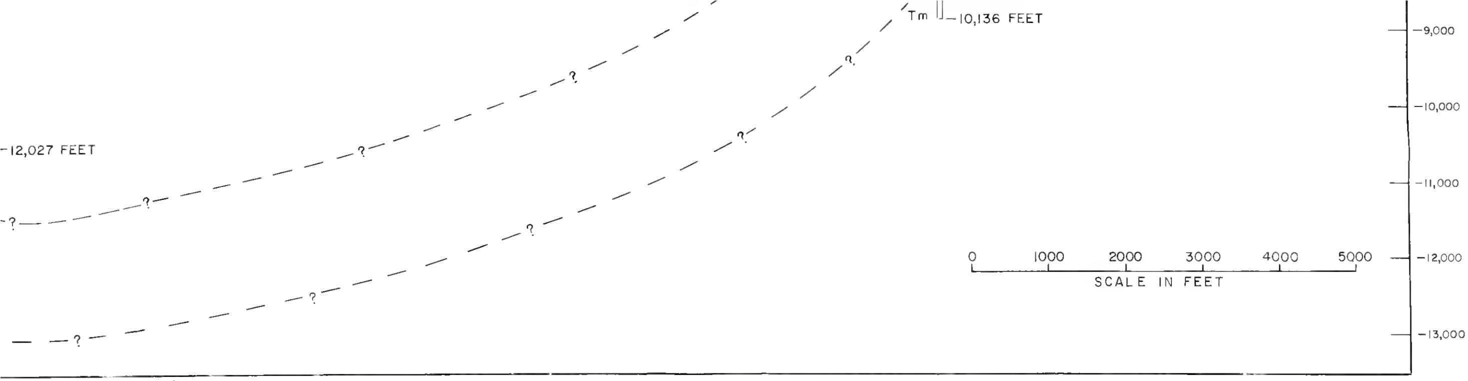


SECTION B-B'

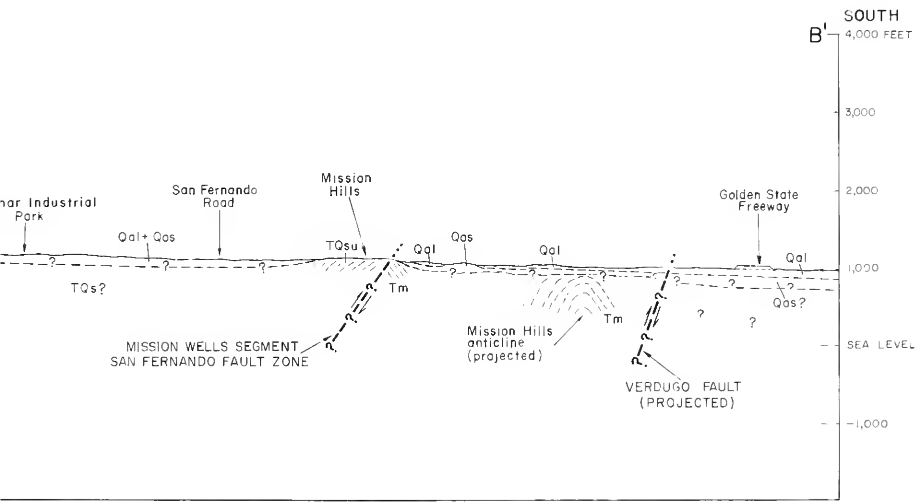
GEOLOGIC CROSS-SECTIONS OF THE SYI

UTILIZING DATA COLLECTED IN STUDY OF

by F. Harold Weber,



ECTION A-A'



EXPLANATION

ROCK UNITS

Qal	Alluvium
Qf	Alluvial fan deposits
Qos	Older alluvium of the Sylmar inlier
Qal + Qos	Younger and older alluvium of the Sylmar inlier (undivided)
Qp	Pacoima Formation
TQs	Saugus Formation (undivided)
TQsu	Upper member of Saugus Formation
Tsr	Sunshine Ranch member of Saugus Formation
Tp	Pico Formation
Ttp	Towsley and Pico Formations (undivided)
Tt	Towsley Formation
Tm	Modelo Formation
bc	Basement complex

OTHER SYMBOLS

ts	Surface on which Towsley Formation was deposited

For further explanation of symbols, see plate 2.

Note: Figure 2 (Weber) in text is cross-section C-C'.

F THE SYLMAR-SAN FERNANDO AREA,

I STUDY OF SAN FERNANDO EARTHQUAKE

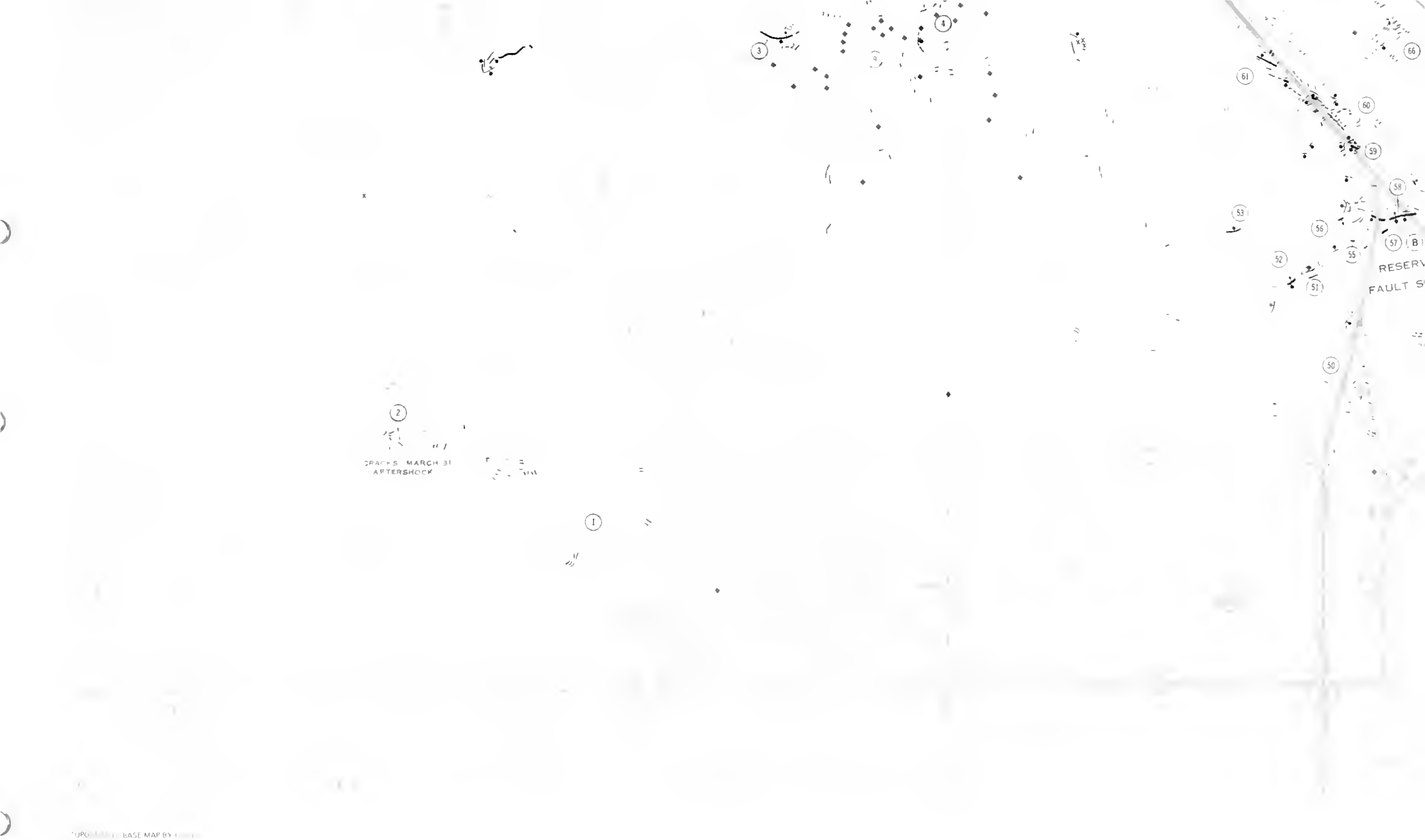
F. Harold Weber, Jr

CALIFORNIA DIVISION OF MINES AND GEOLOGY
WESLEY G. BRUER, STATE GEOLOGIST

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF CONSERVATION

PREPARED I
COUNTY OF LOS ANGELE
AND THE LOS ANGELES

PREPARED IN COOPERATION WITH THE
NTY OF LOS ANGELES DEPARTMENT OF COUNTY ENGINEER
D THE LOS ANGELES COUNTY FLOOD CONTROL DISTRICT



EXPLANATION OF HOUSE DAMAGE SYMBOLS

(by James E. Slosson)

- ◆ HOUSE VACATED DUE TO EXTENSIVE DAMAGE
- · REFER TO NOTES BELOW

NOTES ON AREAS OF GENERAL DAMAGE TO HOUSES

1 *Sunland Tujunga area* Damage primarily in older homes constructed on loose to poorly consolidated alluvium that was subject to consolidation and/or slumping

2 *Kagel Canyon area* Primarily older homes, some masonry structures. Many were constructed on non-engineered fill placed on stream alluvium and/or slopewash. High damage generally associated with failure of non-engineered fill and/or alluvium or slopewash

3 *Foothill Boulevard near Paxton* Primarily older homes located on alluvium adjacent to zone of surface rupture associated with faulting

4 *Maclay-Foothill to Hubbard-Glenoaks* Generally older homes on alluvium in zone of surface rupture associated with faulting

5 *Hubbard-Phillips to Sayre-Fellows* Generally older homes constructed upon alluvium and adjacent to rupture zone cited in Item 4 above

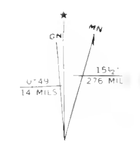
6 *Hubbard-Rajah-Candlewood area* New housing project in zone of surface rupture associated with faulting

7 *Area between Hubbard Street, Foothill Boulevard and Olive View Hospital-Veterans Hospital* New homes in north portion, generally older homes in the south portion. Zone of intense ground shaking and associated lurching. Structures founded on alluvium damaged more than those on engineered fill or bedrock. Apparent ground rupture occurred south of general zone of destruction and the elevated mountain block to the north. Design a primary factor for new homes severely damaged

8 *Roxford-Foothill area* In general, similar to Item 7 above; homes of primarily older vintage

9 *Knollwood-Balboa area* Tracts completed in late 1950s to early 1960 (pre-1963), failures primarily associated with fill settlement and/or failure. Fills failed as a result of consolidation of underlying alluvium or slopewash or slip failure along fill-alluvium contact

10 *Central San Fernando (Maclay Avenue and Mission Boulevard near San Fernando Road)* In general, older structures (pre-1933) many masonry or adobe. Zone of relatively intense ground shaking associated with alluvial foundation materials and a possible high water table



UTM GRID AND 1966 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SURFACE EFFECTS MAP OF THE SAN FERNANDO EARTHQUAKE AREA

by

A. G. Barrows, J. E. Kahle, F. H. Weber, Jr.,
R. B. Saul, and D. M. Morton

1974

SCALE 1:24 000

CONTOUR INTERVAL 25 AND 40 FEET
DOTTED LINES REPRESENT 5, 10 AND 20 FOOT CONTOURS
DATUM IS MEAN SEA LEVEL

EXPLANATION OF MAGNETOMETER SURVEY AND FINDINGS

(by Rodger H. Chapman and Gordon W. Chase)

A ⊢——⊣ A′

Magnetometer profile location

?.......................?

Possible concealed fault zone

Fault trace formed during earthquake. Solid where well defined, dashed where poorly defined.

Ground cracks and other breaks not directly attributable to faulting. Solid where continuous, dashed where continuity is poor, queried where air photo interpretation used for breaks subsequently obliterated.

Fault trace or ground crack showing amount of vertical displacement in centimeters, ball on downthrown side.

Fault trace or ground crack showing relative direction and amount of lateral displacement in centimeters.

DRAFTED BY ALEX ENG AND RUSSEL MILLER 1972
DOROTHY FONG 1973
MAPPING OF SURFACE EFFECTS WAS DONE 1971 1972

EXPLANATION OF SURFACE EFFECTS

Fault trace or ground crack showing relative direction and amount of transverse displacement, shortening is implied where arrow crosses trace, tension is implied where arrow starts at trace

Direction and angle of dip of fault plane or dip inferred from surface breaks

T_3

Backhoe trench, (see Chapter 5G)

Sand boils

x

Shattered ridge tops

(17)

Numbered location referred to in text

(S)

Location where prominent scarp in unconsolidated material is readily visible but may be ephemeral

(B)

Location where prominent scarp in bedrock is visible

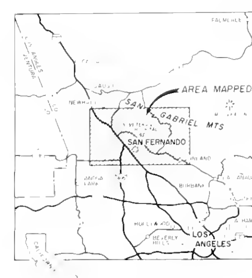
(F)

Location where older rocks can be seen thrust over alluvium or younger rocks by an amount greater than the most recent movement

Landslides or areas of extensive rockfalls

Rockfalls

Some areas were not covered in detail or not visited. Therefore areas lacking data may contain some features similar to those depicted. Landslides and rockfalls were identified on aerial photographs, coverage was not complete and landslides off the north and east edge of the map are not shown (see Morton, this Bulletin)



Index map showing location


118 32'30"
Newhall
Oil Wells
Historic Refinery
Oil Tanks
S A N F R A N C I S C O
M O U N T A I N S
SAN GABRIEL MTS
Whitney
Canyon
Elsmere
Weldon
San Fernando Pass
Fremont Pass
Tunnel
GRAPEVINE FAULT
GRANT
BOUNDARY
ANTICLINE
Mission Point
Jensen Filtration Plant
Substation
Powerhouse
SOUTHERN

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF CONSERVATION

PREPARED IN COOPERATION WITH THE
COUNTY OF LOS ANGELES DEPARTMENT OF COUNTY ENGINEER
AND THE LOS ANGELES COUNTY FLOOD CONTROL DISTRICT

GEOLOGIC MAP OF THE SAN FERNANDO EARTHQUAKE AREA

1974

by A. G. Barrows, J. E. Kahle, R. B. Saul and F. H. Weber, Jr.

SYMBOLS

...d and accurately ...lting Feb 9, 1971 ...hown by arrow

...entified and ac- ...rface faulting Feb ...ed

...ferred and ap- ... Surface faulting ...hown in red

...ral where queried ... data

...erial photographs

... a diffuse zone in ...t is distributed ...uous shear planes

...splacement, U up ...hown by arrow

...ative horizontal

... plunge, dotted

...nge, dotted where

..., dotted where

...dotted where con-

CONTACTS BETWEEN ROCK UNITS

Positively identified and accurately located

Relatively well identified and fairly accurately located

Approximately located

Conjectural or surmised

Concealed

Conjectural contact, concealed, showing probable rock units along contact

DIP AND STRIKE OF BEDDING

Normal

Overturned

Normal approximate

Approximate dip

Vertical beds ⊕ Horizontal beds

Average of crenulated bedding

DIP AND STRIKE OF FOLIATION

Inclined vertical

Representative strike and dip of shear zones

MISCELLANEOUS

(Tt?) Parentheses indicate rock unit shown is surmised to lie beneath alluvium

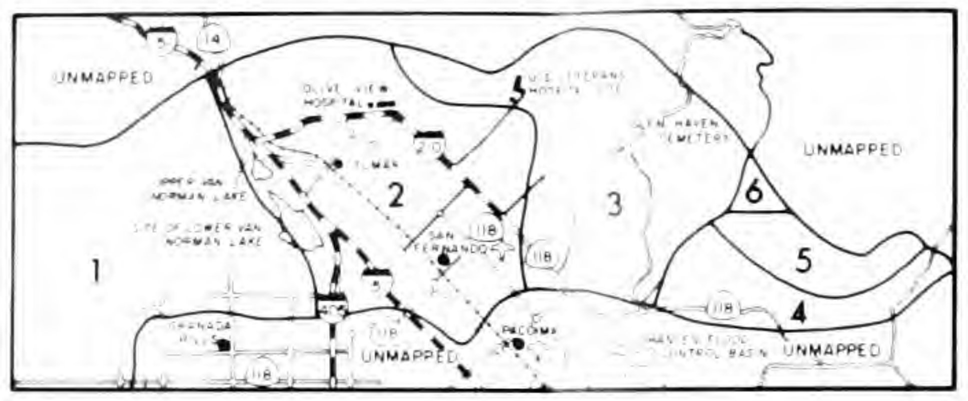
ts Towsley Formation surface (ts) remnants of northeast-tilted very late Miocene seacliff in basement rocks along which occurred farthest inland deposition of Towsley Formation (Weber, text)

B Selected exploratory wells for petroleum (Weber, text)

A A' Geologic cross-section A-A' and B-B' plate 5, C-C' (Weber, text)

Tsr Points to outcrop too small to be outlined

INDEX TO GEOLOGIC MAPPING



Geology mapped by
1. R. B. Saul, 1966-67, 1971-1972
2. F. H. Weber, Jr., 1971-1972
3. A. G. Barrows, 1971-1972
4. J. E. Kahle, 1971

Geology for other areas was compiled from R. L. Beatie, 1958, (area 5) and G. B. Oakeshott, 1958, (area 6) partly revised from aerial photographs by J. E. Kahle.

EXPLANATION

SEDIMENTARY AND VOLCANIC ROCKS

QUATERNARY — Holocene — Continental

af *Artificial fill.* Some was locally faulted and cracked during San Fernando earthquake; structures built wholly or partly on fill commonly damaged.

Qls *Bedrock landslides (uncolored),* most commonly are slumps, probably range in age from Holocene to Pleistocene; slides caused by or reactived by earthquakes are also shown on surface break map, plate 3, as are rockfalls. Arrows denote direction of movement where known; red arrows indicate renewed activity during earthquake. In western area of map Qls (colored) denotes colluvial deposits of probable landslide origin (Saul, text).

Qal *Younger alluvium and colluvium (undifferentiated),* mostly unconsolidated to poorly consolidated fine to coarse sand and gravel; includes deposits of present stream channels, alluvial fans and flood plains (now mostly controlled by flood control dams); deposits generally are finer grained in western area of map, and coarser grained in central and eastern parts (east of Mission Hills). Deposits were faulted, uplifted, and tilted by San Fernando earthquake. Includes following varieties where differentiated:

Qsc *Present stream channel deposits,* generally coarse to very coarse, and unconsolidated

Qf *Alluvial fan deposits,* generally coarse and unconsolidated

Qals *Mostly flood plain deposits,* of the Sylmar inlier, San Fernando Valley, fine- to coarse-grained, generally unconsolidated; includes also some older alluvium interspersed with younger deposits (Weber, text)

Pleistocene

Qoa *Older alluvium and colluvium (undifferentiated),* ranges mostly from fine to coarse sand and gravel, unconsolidated to moderately consolidated, with brown and brownish-red, clay-bearing soils common; previous to earthquake had been faulted, uplifted, dissected and/or tilted; fault displacements may be as much as several hundred feet. Includes following varieties where differentiated:

Qt *Terrace deposits,* perched remnants of older alluvium whose edges commonly sloughed off from shaking during earthquake (Barrows, text)

Qdf *Debris flow deposits,* between upper Marek Canyon and Little Tujunga Canyon (Barrows, text)

Qoc *Older colluvial and debris flow deposits,* beneath Tujunga fault segment; typically red-weathering

Qof *Older alluvial fan deposits*

Qc *Caliche-cemented colluvium,* Oat Mountain area; dash and rectangle symbol for traceable carbonate layers (Saul, text)

Qos *Older flood plain deposits,* of the Mission Hills and Sylmar area (Weber, text)

"THRUST SEQUENCE" - BENEATH LAKEVIEW FAULT SEGMENT (Kahle, text)

Pleistocene-Holocene

Qbx *Breccia deposits,* sedimentary deposits of angular shale chips and colluvium derived from the Modelo Formation, partly tectonic in origin

Qab *Alluvium-breccia deposits,* fluvial fine- to coarse-grained sand and well rounded pebble gravel mixed with angular shale chips and colluvium derived from the Modelo Formation; common debris flow deposits; rare caliche

Qot *Older terrace deposits,* bouldery cobble gravel and interbedded coarse sand and fine-pebble gravel; well rounded clasts

NONMARINE AND MARINE SEQUENCE OF SEDIMENTARY ROCKS, COMMONLY MODERATELY TO TIGHTLY FOLDED AND OVERTURNED; FAULT DISPLACEMENTS MAY BE AS MUCH AS THOUSANDS OF FEET

Continental

Qp *Pacoima Formation,* (Oakeshott, 1952) Olive View - Pacoima Canyon area; vaguely to distinctly layered conglomerate with uncommon sandstone layers; moderately well consolidated to poorly cemented; lies disconformably(?) on upper Saugus Formation below, and is similar to that unit, except that angular to subangular constituents of Pacoima Formation were derived locally from igneous and metamorphic rocks of present mountain front area (Barrows, text)

Pliocene — Estuarine

TQs *Saugus Formation* (undivided, eastern area, TQs), mostly sandstone and conglomerate; moderately well consolidated to poorly cemented; constituents are mostly subangular to subrounded fragments of such rocks as anorthosite which are north of the present mountain front (Barrows, text)

TQsu / Tsr *Saugus Formation* (divided, western area). Upper member (TQsu), generally similar to undivided portion to east; upper member grades downward into lower Sunshine Ranch Member (Tsr), which thickens westward from a point below alluvium in the Sylmar area. Sunshine Ranch Member typically consists of greenish or reddish-gray, clay-bearing siltstone and sandstone, along with coarser sandstone and less common conglomerate layers (Saul, text; Weber, text)

TERTIARY

Tp *Pico Formation,* generally pale-gray resistant sandstone and conglomerate, with minor shale and siltstone; fossiliferous; grades downward into Towsley Formation from which it has been distinguished relatively arbitrarily (Saul, text)

Ttp *Towsley and/or Pico Formations* (undifferentiated), central and eastern part of area

Miocene — Late — marine

Tt *Towsley Formation,* (Winterer and Durham, 1962), similar to Repetto Formation, used formerly by workers in area. Pale- to medium-gray sandstone and conglomerate, commonly massively bedded, locally intraformational breccia beds, petroliferous sandstone, some siltstone and silty shale, especially in western part of area (Saul, text)

Tm *Modelo Formation,* diatomaceous to cherty shale and siltstone; sandstone and conglomerate in upper part, which is somewhat gradational with Towsley Formation. Unit is resistant to weakly resistant; landslides common

Middle

Tto *Topanga Formation,* interlayered conglomeratic sandstone, sandstone, and silty shale near western edge of area (Saul, text)

Tv *Extrusive volcanic rocks,* black, compact, vesicular basalt alternating with reddish brown breccia

BASEMENT ROCKS

BASEMENT COMPLEX, IGNEOUS-METAMORPHIC COMPLEX, PRE-TERTIARY TECTONIC HISTORY NOT CONSIDERED FOR THIS REPORT

PRE-TERTIARY

bc *Basement complex* (undifferentiated), includes metasedimentary Placerita Formation of Miller (1934) composed of marble, crystalline dolomite, quartzite, biotite and graphite schist,

m Marble layers, Placerita Formation of Miller (1934)

s *Serpentinite,* tabular body interlayered with foliated metasedimentary rocks composed of highly sheared, slickensided, rounded fragments up to boulder size of light to dark green serpentinized peridotite. North of

TOPOGRAPHIC BASE BY USGS

This map is an enlargement of parts of Oat Mountain San Fernando and Sunland 1:24,000 scale quadrangle maps

Olive Vista Jr High Sch
Sylmar Sch
Trailer Park
Sylmar
Library
Sylmar High Sch
Shopping Center
Water Tanks
St Didacus Sch
Light and Life Sch
Reservoir
WT
Gridley St
Dyer St Sch
SYLMAR FAULT SEGMENT
MISSION WELLS FAULT SEGMENT
PACIFIC
Sugarloaf
Canyon
SAN FERNANDO
M I S S I O N D E
F E R N A N D O
MISSION HILLS ANTICLINE
VERDUGO FAULT
TUJUNGA FAULT SEGMENT
KAGEL
F E R N A N D O
Pacoima
Mission Hills
V A L L E Y
SEPULVEDA
STREET
LOS ANGELES
Haddon Ave Sch
27'30"

PRE-TERTIA
bc
includes metasedimentary Placerita Formation of Miller (1934) composed of marble crystalline dolomite quartzite biotite and graphite schist locally hornfelsic igneous and meta igneous dark diorite gneiss granodiorite light granitic dikes hornblendite migmatite
m
Marble layers Placerita Formation of Miller (1934)
s
with foliated metasedimentary rocks composed of highly sheared slickensided rounded fragments up to boulder size of light to dark green serpentinized peridotite North of Olive View Very rare in San Gabriel Mts
SCALE 1:18,000
1 MILE
7000 FEET
1 KILOMETER
CONTOUR INTERVALS 25 AND 40 FEET
DATUM IS MEAN SEA LEVEL
N
SYNCLINE
GLEN HAVEN MEMORIAL PARK
Cottonwood Glen
Canyon
LAKEVIEW
FAULT
SEGMENT
LAKEVIEW
TUJUNGA
VALLEY
LOS ANGELES
EX MISSION DE SAN FERNANDO
TUJUNGA
Tujunga
Stonehurst
22'30

p. 6435